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Multi-criteria assessment of biomethane production from waste and residual feedstocks of Emilia-Romagna (Italy)

Giovanni Zanaroli

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Author: Giovanni Zanaroli

Supervisor: Åke Nordberg, Department of Energy and Technology, SLU
Assistant supervisor: Niclas Scott Bentssen, University of Copenhagen, Department of Geosciences and Natural Resources Management
Examiner: Björn Vinnerås, Department of Energy and Technology, SLU

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Abstract

Biomethane can be produced by anaerobic digestion of residues or wastes and it can be used as a renewable fuel for transport. It is associated with reduced GHG emissions, offsetting of fossil fuels and of mineral fertilizers, waste management and nutrient recycling in agriculture. Six suitable feedstocks for the production of biomethane are compared through a multi-criteria assessment designed by the Linköping University and applied to the context of Emilia-Romagna region in Italy. The aim of this work is to provide decision-making support on the choice between feedstocks by identifying opportunity, technical feasibility and environmental sustainability of producing biomethane out of them. Feedstocks availability, current uses and accessibility in relation to the case study are assessed. In addition, technical aspects such as suitability for anaerobic digestion, biomethane yields and digestate quality, are complemented by a life cycle assessment including climate impact and energy balance for each feedstock. The results suggest that there are strengths and weaknesses for every feedstock and that the choice depends on the objective to be achieved and on the specific conditions. In a nutshell, the agricultural feedstocks considered (cow manure and wheat straw) and the agro-industrial (milk and cheese industry by-products and wine industry by-products) respectively have very high and medium theoretical availability and poor or satisfactory suitability for production of biomethane and biofertilizer through single-feedstocks digestion. Organic municipal solid waste (OMSW) and pig slaughterhouse wastes (PSW) have low theoretical availability but are well suitable for the production of biomethane. PSW is also well suitable as biofertilizer. From an environmental point of view, PSW and OMSW are associated to the best performances and liquid manure to the worst if the assessment is done according to the RED guidelines. By applying a system expansion to the environmental assessment different outcomes were obtained and the sensitivity of the parameters chosen was studied through sensitivity analysis. To conclude, the production of biomethane from the selected feedstocks can relevantly contribute to the regional targets for the transport sector and the methodology of this assessment is useful to deal holistically with the feedstock-choice while providing decision-oriented information.

Abstract (Italiano)

Il biometano può essere prodotto tramite digestione anaerobica a partire da substrati o matrici residuali e di scarto ed essere utilizzato come combustibile rinnovabile per il trasporto. E' associato alla riduzione delle emissioni di gas a effetto serra, alla sostituzione dei combustibili fossili e dei fertilizzanti minerali, alla gestione dei rifiuti e al riciclo dei nutrienti in agricoltura. Sei substrati da adibire alla produzione di biometano sono confrontati attraverso un analisi multi-criteriale ideata dall'Università di Linköping e applicata al contesto della regione Emilia-Romagna in Italia. Lo scopo di questo lavoro è di provvedere supporto nella scelta fra le diverse matrici tramite l'identificazione della loro disponibilità, della fattibilità tecnica e della sostenibilità ambientale della produzione di biometano a partire da esse. La disponibilità dei substrati, gli usi correnti e l'accessibilità in relazione al caso studio sono considerate. Agli aspetti tecnici -come la compatibilità per la digestione anaerobica, la resa in metano e la qualità del digestato- è aggiunta una analisi ambientale del ciclo di vita che include l'impatto climatico e il bilancio energetico per ogni substrato. I risultati evidenziano punti di forza e debolezze per ciascuno dei casi considerati e la scelta fra essi dipende dagli obiettivi che si vogliono raggiungere e dalle condizioni specifiche. In estrema sintesi, si può dire che le matrici agricole considerate (letame e liquame bovino e paglia da frumento) e quelle agro-industriali (residui lattiero-caseari e residui di vinificazione) presentano, rispettivamente, disponibilità teoriche molto e mediamente alte in regione ma si prestano in modo scarso o soddisfacente alla produzione di biometano e di bio-fertilizzante nel caso di mono-digestione. La frazione organica dei rifiuti differenziati (OMSW) e gli scarti di macellazione suina (PSW) sono disponibili in scarse quantità ma si prestano bene dal punto di vista tecnico. I PSW presentano anche una buona qualità del digestato. Attenendosi alle linee guida della RED, PSW e OMSW risultano avere le migliori performance dal punto di vista ambientale, mentre il liquame bovino la peggiore. Inoltre, le variazioni dei risultati in seguito a espansione del sistema e sensitivity analysis sono discusse. Per concludere, il contributo potenziale dei substrati considerati per il settore dei trasporti regionale e per la riduzione delle emissioni a effetto serra si è dimostrato elevato e la metodologia utilizzata è particolarmente adatta per affrontare olisticamente la complessità del tema e ottenere, al tempo stesso, chiare indicazioni decisionali.

Popular summary

Today, everybody seems to be aware that our society would need to get rid of its dependency on fossil resources because of the disastrous consequences on the environment. The plastic floating in the oceans and climate change are by now part of the daily discussions and they are a source of deep concern for many people. The transport sector has played an important role for the situation where we are now: the extraction and burning of fossil fuels by cars, trucks, planes and boats are relevantly contributing to climate change, as I explain in the introduction (Section 1.1).

Several solutions and alternative fuels for the transport sector have been proposed. One of the most promising and fast-growing solutions in the world is biomethane, also known as biogas. Biomethane is not different from natural gas (98 to 100% methane) except that it is self-produced with a biological process instead of being extracted from underground prehistoric reserves. Some micro-organisms are able to produce methane and other gasses out of organic feedstocks (such as food, plant material, animal manure etc.). Biomethane can be used as a transport fuel, as well as for other uses; the liquid residue of the process (digestate) is rich in carbon and nutrients and can be used in agriculture.

Switching from a fossil fuel to biomethane reduces importantly the climate impact of a vehicle, especially if biomethane is produced out of recycled feedstocks such as waste and agricultural or industrial residues. However each feedstock is associated to a different performance in terms of quantity and quality of the products obtained and to a slightly different process. In this work, I've dealt exactly with those issues: the performances of six different feedstocks were compared from a technical and environmental point of view through a mixed set of methods, including literature review and Life Cycle Assessment approach. In order to select the feedstocks, I investigated the availability of many residual feedstocks in the Italian region of Emilia-Romagna. Not only the theoretical availability of each feedstock, but also the geographical distribution and the “real” availability -determined by accessibility, seasonality and competing uses of the feedstock- were investigated.

What I could get out of this analysis is that the agricultural feedstocks considered (cow manure and wheat straw) are very abundant and available in the region, hence they can contribute relevantly to the production of biomethane. The availability of other feedstocks in Emilia-Romagna is much more limited, but it is in some cases (for example for pig slaughterhouse wastes) partly compensated by a high specific yield of biomethane and a high nutrient content of the digestate. Overall, the use of biomethane produced out of any of the feedstocks considered except for one (cow liquid manure) would lead to a reduction of at least 50% in greenhouse gas emissions compared to the use of fossil fuels (diesel or gasoline), according to the conditions assumed in this study.

In short, the availability of suitable feedstocks for its production -together with the simplicity of the process and the environmental benefit- stresses the interest for biomethane development in the region and at larger scale. A comprehensive analysis including and expanding the scope of this work is recommended in order to select the optimal feedstocks for production of biomethane and before any implementation is carried out. To conclude, I believe that biomethane might not save the world alone but it is definitely worth a try!

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Abbreviations

CRPA	Centro Ricerche Produzioni Animali (Research Centre on for Animal Production)
ILUC	Indirect Land Use Change
ISTAT	Italian National Statistics Institute
LCA	Life Cycle Assessment
MCA	Multi Criteria Assessment
OMSW	Organic fraction of Municipal Solid Waste
PE	Primary Energy
PEIO	Primary Energy Inputs to Outputs ratio
PSW	Pig Slaughterhouse Waste
TS	Total solids (Dry matter)
VS	Volatile solids (Organic dry matter)
WW	Wet weight

1 Introduction

The relevance of the topic of this report is introduced in Section 1.1. The bigger picture is presented, with drivers such as climate change and the transport sector affecting the global situation and calling for solutions. Biomethane is contextualized among the biofuels and the state of the art of literature about biomethane feedstocks is provided. In Section 1.2, the research objectives of this report are presented, followed by a summary of the main criteria and parameters adopted. In Section 1.3, the limitations of the assessment are outlined.

1.1 State of the art

CO_2 emissions from the transport sector accounted for 23% of the global energy-related emissions in 2014 and have been increasing by 2.5% annually between 2010 and 2015, according to the report released in October 2018 by the Intergovernmental Panel on Climate Change (IPCC, 2018). The transport sector is the least diversified sector, with an almost complete reliance on oil products for its energy needs and therefore contributing relevantly to the global oil final-energy demand (ibid., Fenton & Kanda, 2017).

Biofuels have become a topic of interest in the last few years in connection with the struggle to mitigate GHG emissions and to reduce the dependency on fossil fuels associated to the transport sector. Even though the global production of biofuels is still limited today compared to the production and use of fossil fuels, biofuels are perceived by many as a "bridge", as a complementary solution or even as an alternative to electric vehicles and to other solutions for the transport sector of the future (Börjesson *et al.*, 2009; Magnusson & Berggren, 2018). Among the scenarios drawn by international scientists and policy makers for the reduction of CO_2 emissions in the transport sector by 2050, biofuels often figure as a key element for decarbonization and in particular for heavy-duty vehicles, aviation and shipping (IPCC, 2018).

At the same time, the category of biofuels has received severe critics in the past years. One of the main arguments which were brought up by several NGOs and researchers is ethical, and it concerns the indirect change of land use (ILUC) and the exploitation of resources for the purpose of growing energy crops instead of food crops, while poverty and food scarcity still affect a large part of the global population (Börjesson *et al.*, 2009; Scarlat *et al.*, 2018). Another argument along this line concerns the sustainability of biofuels in terms of emissions reduction, especially for the case of imported biofuels or biofuels produced with feedstocks coming from remote areas of the world (Börjesson *et al.*, 2009; Åhman, 2010).

The critics against unethical and unsustainable biofuels have contributed to shift the interest from the so called "food-based" or "first-generation" biofuels to "advanced" or "second-generation" biofuels. Advanced biofuels are produced out of materials at the end of their life cycle, such as bio-wastes, residues and by-products (Mitkidis *et al.*, 2018). In order to disincentivise or phase out the production of food-based biofuels, policy efforts are being made (Scarlat *et al.*, 2018). In the Renewable Energy Directive of the EU (RED I) from 2009, waste-based biomethane is double-counted in the calculations for the achievement of national targets in sustainable transport. Compared to the RED I, it was announced that the upcoming RED II for the period 2021-2030 will tackle the issue more directly (Mitkidis *et al.*, 2018). One of the measures expected is the setting of a decreasing cap (starting from 7% and reaching 3.8% in 2030) on the maximum contribution of food-based biofuels to the renewable energy targets (Bitnere, 2017; European Commission, 2016).

Biomethane is gaining quite a lot of attention in the past recent years among the second-generation biofuels. Biomethane is obtained after upgrading (removal of carbon dioxide) of biogas, which is produced by anaerobic digestion of any biodegradable feedstock.When the feedstocks used are bio-wastes, residues or by-products, the biomethane produced can be considered "advanced". Biomethane is primarily interesting for use as a transport fuel with the purpose of replacing fossil fuels and reducing emissions. Furthermore, anaerobic digestion also generates a nutrient-rich co-product (digestate), which can be used as an organic fertilizer and offsetting mineral fertilizers by making agronomic use of the digestate (Patterson *et al.*, 2011).

Which feedstocks is best to use for the production of biomethane is an important question among the issues which are being debated. Research has already been made over many aspects of biomethane production, use and implementation. Hijazi *et al.* (2016) asserts that "the type of feedstock is a determining factor for the environmental impacts of biogas systems".

Recent studies have looked into feedstocks available at different scale, assessing potential energy contributions, technical suitability for biomethane production, associated environmental benefit, public opinion and economic profitability (Åhman, 2010). However, there is a lack in comprehensive and systematic studies which are able to consider "the full picture" when comparing different feedstocks for biomethane production (Ammenberg *et al.*, 2017).

1.2 Research objectives

In this report, a multi-criteria assessment is carried out for different waste-based feedstocks which can be used for the production of biomethane. Feedstock availability, technical suitability and environmental sustainability are investigated.

The region Emilia-Romagna, situated in the Po Valley of northern Italy, is taken as a case study for this report. Emilia-Romagna became one of the pulling regions for biogas development in Italy in the recent years and has been referred to as a potential "biomethane hub" due to some favourable characteristics described in the background (Patrizio & Chinese, 2016). The national incentive scheme, in force since March 2018 as part of the Biomethane Decree, aims at enhancing production of biomethane from wastes and by-products (Ministero dello Sviluppo Economico, 2018). Hence, a multi-criteria comparison between some of the relevant waste-based feedstocks available in the region recently became of great actuality.

In this study, the multi-criteria assessment (MCA) is carried out for different waste-based feedstocks, which can be used for the production of biomethane and is based on the following research questions:

1. What is the availability of the selected feedstocks within the Italian region of Emilia-Romagna?
2. What is the technical suitability of the selected feedstocks for the production of biomethane and bio-fertilizer through anaerobic digestion?
3. Is it reasonable from an energy and environmental perspective to produce biomethane from the selected feedstocks?

The aim of this work is to provide decision-making support for public and private bodies on the choice between waste-based biomethane feedstocks by identifying opportunities and discussing their feasibility and environmental sustainability.

The criteria included in the MCA are socio-geographical, technical and environmental. For the socio-geographical aspects, theoretical and real availability of the feedstocks are considered, as well as their geographical distribution and accessibility in the region. For the technical aspects, methane yield, nutrient content, suitability for anaerobic digestion and suitability for the use as bio-fertilizer are considered. For the environmental aspects of biomethane production from the feedstocks, the net energy balance between inputs and outputs as well as the climate impact (in terms of GHG emissions) are assessed.

1.3 Limitations of the study

The feedstocks selected for the MCA of this report are:

- Organic fraction of municipal solid waste (OMSW)
- Cow manure
- Pig slaughterhouse waste (PSW)
- Wheat straw
- Milk and cheese industry by-products
- Wine industry wastes

The report is limited to the Emilia-Romagna region and to present time. Concerning the process, it is assumed that each feedstock is used individually and not in co-digestion with other feedstocks. The biomethane produced is assumed to be upgraded and used as a fuel for transport, while the digestate produced is assumed to be used, at least for the solid fraction, as bio-fertilizer in agriculture.

2 Background information

Section 2.1 provides background information about characteristics and production of biomethane, followed by a short summary concerning technological development and possible uses of the gas, and by an introduction to the role played by digestate for the recycling of nutrients. Sections 2.2 and 2.3 provide, respectively, background information about the six feedstocks investigated and about the case study. Section 2.4 introduces the approach of Multi Criteria Analysis in the context of system analysis and provides in-depth background information about the parameters considered in the assessment.

2.1 Definition and history of biomethane

What is biomethane

Biomethane is an upgraded version of biogas, which -instead of being composed by methane (roughly 60%), carbon dioxide (roughly 40%) and other gasses- is purified to almost 100% methane. As also biogas, biomethane is the product of microbiological degradation of organic substrates under anaerobic conditions.

The process of methane formation consists of four main steps, which depend on different consortia of microorganisms (Weiland, 2010). During the first two steps -hydrolysis and fermentation- the complex organic materials are reduced to simpler form and transformed in intermediary products (such as alcohols, fatty acids, lactic acid and also hydrogen gas and carbon dioxide) thanks to strict anaerobic and facultative anaerobic bacteria (ibid). Then anaerobic oxidation takes place and all fatty acids are converted to hydrogen gas and carbon dioxide or to acetate. During the fourth step, methane formation, two syntrophic groups of microorganisms (respectively, hydrogen and acetate users) convert the obtained components to methane (ibid.).

Once that methane is formed, the gas is purified from carbon dioxide and from other gaseous co-products of methane (i.e volatile nitrogen). This step, known as

"Upgrading", can be done in several ways and with different technologies. The most common upgrading technologies are high-pressure water-scrubbing and membrane technologies (i.e ammine membrane). The carbon dioxide which is sequestrated can be collected and re-used for example in soft drinks industry or algae breeding, so that the release to the atmosphere can be avoided. Depending on the transport system and on the final use, the upgraded gas needs to be compressed to a certain pressure. Alternatively, biomethane can be liquified.

Digestate, the co-product of biomethane, needs to be handled once that the anaerobic digestion phase is over (approximately after 30 days). Depending on its characteristics and on factors such as the distance from the field where it will be spread, digestate can be handled differently. The most straightforward pathway is to transport and spread the digestate the way it is after anaerobic digestion, however a phase-separation step is often introduced in order to separate the liquid phase from the solid and circulate it in the digestor, so to reduce the volumes which need to be transported to the field. Different separation technologies have different separation efficiencies in terms of nutrients accumulation: for example, decanter and discontinuous centrifuges are associated to higher efficiency than screw press (Drosg *et al.*, 2015). In addition, further treatments of the solid and liquid phases can be applied in order to enhance the availability of the nutrients and other characteristics of the digestate (ibid).

Biomethane as an energy carrier and a green fuel

Biogas is well known and produced since the 1950s. At that time, biogas was considered as a by-product of processes such as waste water treatment and generally it was unused or used to heat the buildings around the production site. In the 1990s, after the oil crises and the raising of environmental concerns, biogas started to gain interest as a potential renewable energy source. It has been used for heat and electricity generation.

More recently, upgrading to biomethane was implemented in order to valorise the gas better than as raw gas. Once upgraded and compressed or liquified, biomethane can replace carbon natural gas (CNG) -as transport fuel for CNG vehicles and as gas for domestic uses- or be used for the generation of electricity.

Biomethane can be stored and can be transported through the existing gas grids or by truck. It is appreciated for being a renewable source of energy and being less dependent on climatic conditions than other renewable forms of energy (i.e wind and solar power).

Agronomic use of digestate and circular economy

What is also fascinating about biogas production is its transboundary and cyclic nature. During biogas production, feedstocks at their end-life such as municipal organic waste, agricultural residues and industrial bio-wastes are used as feedstocks for the anaerobic digestion. Everything which is not fermented to biogas during anaerobic digestion ends in the digestate. Digestate has little methanogenic potential but can be used in agriculture due to its content of carbon, macronutrients (nitrogen, phosphorus and potassium) and micronutrients.

In this way the cycles of materials at their end-life can be closed and materials normally requiring a disposal cost can gain an economic value. From an environmental point of view, the recycling of nutrients through spreading of the digestate is also interesting because it can contribute to the offset of mineral fertilizers.

2.2 The investigated feedstocks

It is defined "feedstock" any substance or material which can be used as primary input for the process of biomethane production. The feedstocks investigated in this report are wastes and residues available in the region. It is defined "residue" any substance or material which is not deliberately produced during a production process (Ministero dell'ambiente e della tutela del territorio e del mare, 2017). No distinction is made in this report between the terms "by-product" and "residue". According to the Italian regulation (ibid), a residue is characterized by: 1) being originated from a production process which is not primarily aimed at producing the feedstock; 2) to have some utilization besides disposal; 3) to not require further treatment ; 4) to be legal, by fulfilling the requirements contained in the health and environmental legislation. All the investigated feedstocks belong to the category of residues except for the organic fraction of municipal solid waste (OMSW).

OMSW belongs to the category of wastes. It corresponds to the sorted fraction of organic municipal waste in the region and is a synonym of the term "catering waste". Besides households organic waste, OMSW also includes food waste from restaurants and canteens and small garden residues such as grass, fruits and leaves. However, abundant residues from gardening and from tree pruning belong to the green fraction of waste, which is excluded from this assessment. OMSW is subject to the waste-management regulation, which implies a longer path necessary to obtain authorization for a new plant and also the ban to use digestate as fertilizer (Ministero delle politiche agricole alimentari, forestali e del turismo, 2016; Croce, 2018). In the case study, 61.8% of the total urban waste is source-separated in different wet fractions (organic and green fractions) and dry fractions (paper, plastic, glass and metal fractions) according to the 2017 report on waste management from the Regional Agency for Prevention, Environment and Energy (Zinoni *et al.*, 2017). The OMSW fraction corresponds to about 15% of the total sorted-waste (ibid). The most common collection method for OMSW in Emilia-Romagna is the door by door collection (50.8%), followed by street containers (41.8%) and by other services.

Cow manure includes manure from meat and dairy livestock of the region mixed with straw or other bedding material used in the stable. Cow slurries are also considered in the assessment when specified and referred to as “Cow liquid manure”. The difference between the two, despite the same origin, is due to the mixture with animal bedding in the solid part, which alters the composition and the physical characteristics of the feedstock.

Pig slaughterhouse waste (PSW) includes the main types of residues from the pig slaughterhouse industry: offal, guts, blood, bristles, nails and bones. The characteristics refer to a mixture of these parts, or to only some parts if specified. As required by the legislation, plants using animal wastes for biogas production have to be registered by the National Veterinary Authority. PSW which are not considered to belong to the category of “animal wastes with low hygiene sanitary risk” according to Reg. CE n. 1069/09 and Reg. CE n. 142/11 have According to the EU regulation (Reg. CE n. 1069/09), residues of animal origin are divided in three categories based on the hygiene sanitary risk. Meat and bones flours fall into Category 2, while all the rest of PSW fall into Category 3. A requirement for residues belonging to Category 3 is pasteurization prior to further uses, which consists of heat treatment (70°C) for one hour (Riva *et al.*, 2013).

Straw from cultivation of soft wheat (*Triticum aestivum*) is considered. In the case study, straw is either left on the field after harvest or collected and used for other purposes. Straw from other cereals (for example durum, barley and sorghum) was excluded from the assessment unless specified.

Milk and cheese industry residues include whey and ricotta whey (*scòtta* in Italian). Whey is the liquid residue obtained when casein and fat are separated by coagulation from the milk, ricotta whey is the residual liquid after extraction of proteins and fat from the milk. Where not specified differently, the values used in the report refer to whey from cow milk. Further residues or by-products which were not included due to lack of data are buttermilk, unsold milk and cheese, cleaning and waste waters from the factories. The feedstock is referred to as “whey” throughout the report.

Wine industry residues includes all residues from the wine making process. The main residues are: grapeseed, marcs, stalks and grape lees. When not specified differently, the values refer to a mix of all the sub-fractions of the feedstock.

2.3 The case study (Emilia-Romagna)

Emilia-Romagna is a region of 22,452,78 km^2 located in north-eastern Italy. About half of the territory (48%) is flat, while the remaining territory is hilly (27%) or mountainous (25%) (Cavicchi, 2016). In response to a favourable regime of incentives and tax exemptions and to other factors, the number of biogas plants in the region increased exponentially between 2010 and 2012 (ibid.). The number of biogas plants reached 237 plants in 2018 and accounts for about 15% of the biogas produced in Italy (Caselli, 2018). The distribution of the biogas plants is concentrated in the northern area of the region, which corresponds to the flat part and therefore to the most favourable area for agriculture and for animal production (Valentini, 2018).

The way the biogas sector developed in the region was characterized by a large use of silages and energy crops for production of electricity (Cavicchi, 2016). As in the rest of Italy, biomethane never developed as the upgrading infrastructure necessary for the production of biomethane was never put in place. However, in response to the new national policy for biomethane, the interest is recently shifting towards it and in particular to advanced biomethane (Fontana, 2018).

The transition process from biogas to biomethane is supported by the regional administration, which included biomethane in the 2030 Regional Energy Plan and co-financed two research projects on biomethane development: GoBiom and Biomether. GoBiom was concluded in autumn 2018 and aimed at optimizing the value chain of biomethane, by working on solutions for the upgrading technology and identifying potentials of residual biomasses at regional level (GoBiom, 2018). BioMether is a Life project running until 2019 which also aimed at optimizing biomethane value chain focusing on biomethane from sludge and urban wastes. The presence at regional level of research centres such as CRPA and of several universities seems to contribute in speeding up the process as it happened with biogas development (Cavicchi, 2016). National actors such as Consorzio Italiano Biogas (CIB) and the environmental NGO Legambiente are very active in the region and in the northern part of Italy. Furthermore, the already established use of compressed natural gas (CNG) fuelled vehicles -accounting for about 15-20% of the regional car fleet- and the existing infrastructure for CNG distribution create favourable conditions for the development of biomethane in the area (Patrizio & Chinese, 2016).

2.4 Multi-criteria assessment as a holistic and decision making tool for the choice between feedstocks

Biomethane development is a complex and transboundary issue, which involves knowledge from the agricultural, energetic, environmental and socio-economic fields (Olsson & Fallde, 2015). In order to describe complex issues, a vast amount of information is needed, depending on the degree of observation (ibid.). System analysis is a discipline aiming at the observation of complex issues from a holistic, not sectorial or narrowed point of view. It developed greatly in the last 50 years (Liljenström & Svedin, 2005). System analysis can be useful for scientists, policy makers and other actors to break down an issue into manageable components (Olsson & Sjöstedt, 2004). System analysis was applied to biogas and biomethane development at different levels and in different ways in the past. Several tools, indicators and methodologies have served as "lenses" for system analysis depending on the aspects to be emphasized. One type of system analysis is the multi-criteria assessment of the suitability of a feedstock for production of biogas/biomethane. Pioneers in this type of analysis were some researchers from the Biogas Research Centre of the Linköping University (Sweden). Several of the aspects addressed in a study by Ammenberg *et al.* (2017) were investigated in this report and are presented in the following paragraphs along with background knowledge.

Assessing feedstocks availability

The theoretical availability of a feedstock can be estimated with reasonable accuracy, however it is not always representative of the real availability of a feedstock, as that depends on factors such as the current uses and the competing interests over it, as well as on its physical and geographical accessibility and on the seasonality during the year.

Assessing feedstocks technical suitability for biomethane production and nutrient recycling

Biomethane represents the most valuable product of anaerobic digestion, from the economic perspective. The biomethane yield is defined as the amount of methane which can be obtained from a ton of volatile solids (VS) of feedstock after anaerobic digestion and upgrading processes. It is expressed as volume (m^3) of gas composed by at least 97-98% of methane. The quality of the feedstock and the process itself affect the biomethane yield (Hijazi *et al.*, 2016). The quality of the feedstock is defined by its biochemical composition and by other characteristics such as TS and VS content. According to Hijazi *et al.* (2016), carbohydrates produce biogas with theoretical methane content of 50%, while biogas from fats and proteins tends to have a CH4 content of up to about 70%. The amount of total solids (TS) is the dry matter content of the feedstock, usually reported as a percentage of the wet weight. Volatile solids (VS) is the fraction of TS which is lost (evaporating) after ignition and is expressed as percentage of TS. The amount of VS corresponds to the organic content within the TS and is the part affected by the microbiological activity and directly correlated to the biogas yield. Other factors such as retention time, loading rate, digestion technology (co-digestion; batch or continuous; one or two phase digestion) and pre-treatment of the raw feedstocks have an influence on the final yield as well (Berglund & Börjesson, 2006).

Nutrients availability, degradability, physical characteristics and presence of inhibiting substances in the feedstock are some of the main factors affecting the anaerobic digestion process. The carbon-nitrogen (C/N) ratio is an indicator of degradability which affects the entire anaerobic digestion phase, by influencing the amount of nutrients available for the microorganisms involved and the process stability (Divya *et al.*, 2015). The highest ratio tends to increase the uptake of nitrogen by microorganisms, while the lower ratio leads to ammonia accumulation and potentially inhibition (Divya *et al.*, 2015). A C/N ratio of the feedstock between 20 and 30 is optimal, while a C/N ratio higher than 30 -typical of feedstocks rich in lignocellulose- normally requires additional pre-treatments to facilitate the digestion process (Ammenberg *et al.*, 2017; Greggio *et al.*, 2018). The pH can affect the process of anaerobic digestion, even though self-regulation and stabilization of the pH usually occur during anaerobic digestion (Consultation with Åke Nordberg 4/7/2018).

The suitability of a feedstock for bio-fertilizer use depends on the quality of the digestate produced. The quality of the digestate is determined by its nutrient content and by the presence and persistency of undesirable substances in it. It is considered undesirable any substance associated to negative effects on plants, soil and living organisms. Typical examples of undesirable substances are plastics and heavy metals. Concerning the nutrient content, the amount of nutrients which remains in the digestate can vary depending on the conditions of the anaerobic digestion process and on the feedstock as well. Literature suggests that all of the Total Phosphorous generally remains in the digestate, while a part of the Total Nitrogen can get lost during the process and during uncovered storage, mainly in the form of ammonia (Güngör *et al.*, 2007; Poeschl *et al.*, 2012). Part of the organic nitrogen in the raw feedstock tends to be transformed to plant-available, ammoniacal form ($N\text{-}NH_4^+$) during anaerobic digestion (Fabbri & Piccinini, 2012; Drosg *et al.*, 2015). When digestate is directly spread as bio-fertilizer the entirety of the nutrients contained by the digestate reaches the soil, but when digestate is separated in phases a large part of the nutrients remains in the liquid phase (the extent of it depending on the separation technology used). Concerning the nitrogen form, the majority of the ammonium nitrogen (around 80%) tends to remain in the liquid fraction of digestate, while the solid fraction is characterized by organic nitrogen (Drosg *et al.* 2015). From a regulatory point of view, in Italy digestate is regulated based on the feedstock of origin. For example when the feedstock sent to anaerobic digestion belongs to the category of "wastes", the resulting digestate will have to be managed in accordance with the normative regulating the use of wastes. These regulatory differences have consequences on the authorization process for the use of digestate as bio-fertilizer.

Assessing the environmental aspects of biogas/biomethane production

The anaerobic digestion of a feedstocks is associated to local and more widespread or climatic impacts (Ammenberg *et al.*, 2017). Local impacts include negative impacts on land/soil, water and ecosystems. They are typically associated to the production of crops used as feedstocks for biomethane production or to the spreading of digestate. Other local impacts such as odour and aesthetic issues might also be included in some assessments. Climatic impacts arise from the whole life-cycle process and correspond to GHG emissions released to the atmosphere. The process includes steps taking place before the incoming feedstock reaches the plant (collection and transportation), during the processing within the plant (pre-treatments, anaerobic digestion, followed by upgrading and compression of the biogas produced) and after leaving the plant (separation of the digestate between solid and liquid form, loading, transport and spreading to field). Each of these steps of the process consumes energy, which is indirectly associated to greenhouse gas (GHG) emissions depending on the source of energy utilized. The sum of these GHG emissions defines the climatic impact of the biomethane produced from the feedstock. Typically it is accounted by including also the direct GHG emissions to the atmosphere which can occur during the process due to leakages or flared biogas/biomethane.

The Renewable Energy Directive (RED) of the European Union from 2009 suggests to account for the GHG emissions of biomethane production in the described way. With the RED approach, the GHG emissions from biomethane production are referred to the Lower Heating Value of the feedstock and compared to the GHG emissions from the production of another fuel (Ammenberg *et al.*, 2017). However in literature it is common to expand the analysis in order to account also for indirect upstream and downstream GHG emissions by using a Life Cycle Approach. Upstream GHG emissions occur during processes prior to collection of the feedstocks (such as the cultivation of agricultural feedstocks). However, according to Manninen *et al.* (2013), no upstream GHG emissions should be accounted for waste-and-residues based feedstocks due to their nature of waste resource. Downstream GHG emissions can refer to avoided emissions as a consequence of producing biomethane and spreading of digestate, or also to emissions occurring because of the change in land use or feedstock use (Tufvesson *et al.*, 2013).

A thing which is important to notice is that the GHG emissions occurring from the use of biomethane (combustion, in the case of transport) are generally not accounted for biomethane produced from plant-based feedstocks or waste-based feedstocks. The reason for this is that the GHG emissions associated to this type of biomethane, which get the name of “biogenic emissions”, were previously sequestrated from the atmosphere by the plants used for production of biomethane or, in the second case, would occur in any case due to the degradable nature of the feedstock . The not-accounting of "biogenic emissions", especially of the ones from plant-based biomethane (i.e biomethane from energy crops or from woody plants) has been criticised by several literature studies on the basis that these emissions could be avoided if the plants were left in place (Searchinger *et al.*, 2009; Haberl *et al.*, 2012; De Kleine *et al.*, 2017).

3 Methodology

In Sections 3.1 and 3.2 of the methodology chapter, the criteria behind the choice of the feedstocks and of the parameters assessed are outlined. In Sections 3.3, 3.4 and 3.5 the methods used to answer the research questions are presented, divided by research question.

3.1 Choice of the feedstocks

The choice of which feedstocks to assess was based on several criteria.

The first criteria was to consider feedstocks which are residues or waste resources. Energy crops and not-residual feedstocks were therefore excluded.

The second criteria was the feedstock availability (in terms of tons of VS per year). The theoretical availability of all residual and waste resources in the region was considered and the feedstocks which were considered to be only marginally significant at regional scale were excluded.

In the third place, the feedstocks category was considered. Urban, agricultural and agri-industrial were the main categories identified. It was chosen to represent them all with at least one feedstock.

The fourth criteria was process uniformity. Feedstocks whose treatment process differs too much from the rest (i.e woody residues) were excluded because of difficult comparability.

3.2 Choice of the parameters

Compared to the broader study from Ammenberg *et al.* (2017), which served as as guiding framework for structuring this assessment, it was chosen to focus mainly on technical and environmental aspects. Geographical and socio-economic aspects were also partly covered in order to contextualize the assessment to the case study and to discuss about the effective availability of feedstocks and Regional impacts.

The structure of the assessment is schematized in Table 1. The three research questions presented in Section 1.2 are addressed with eleven sub-questions, which were assessed by using different indicators, methods and tools. Seven of the seventeen indicators proposed in the original study by Ammenberg *et al.* (2017) were excluded due to time constraints and, partly, due to lack of information available. The indicators which were excluded regarded mostly socio-economic aspects (technological feasibility, profitability, clarity of business implications, policy support and public opinion) and local environmental impacts (impacts on land or soil, on water resources, on biodiversity and ecosystems, other impacts such as odor, noise and esthetic issues, and ILUC).

Table 1. *Research matrix*

Research question	**Sub-question**	**Indicators**	**Method/Tool**
Availability of feedstocks	Amounts per year	Theoretical feedstock (TS) per year	GoBiom database
	Geographical distribution	Feedstock production density sites	GoBiom maps, Biomether geoportal
	Current uses, control and competition	Length of contracts for access to feedstock	Literature review, Stakeholder Interviews
Technical suitability	Physical-chemical characteristics	Biochemical composition; TS & VS	Literature review
	Suitability for a. digestion	C/N ratio	Literature review
	Biomethane yield	B_0 and G_0	Literature review
	Biomethane volume and corresponding energy value	Tot biomethane producible per year	Own calculations
	Suitability as bio-fertilizer	Amount of undesirable substances	Literature review
	Nutrient content	Nitrogen, Phosphorous contents	Literature review
	Amount and value of bio-fertilizer	Nitrogen, Phosphorous available per year	Own calculations
Environmental sustainability	Climate impact	GHGs emissions savings	LCA
	Energy efficiency	Energy balance	LCA

3.3 Assessment of feedstocks availability

Amounts

The Regional database of wastes and by-products was realized in 2017 for the GoBiom Project and was used in this report in order to extrapolate the amounts of feedstocks available within the region. The amount of feedstock available is a new indicator compared to the assessment of Ammenberg *et al.* (2017). The data used refer to the year 2016 and are based on the data from ISTAT, the Italian National Statistics Institute. The amounts of feedstocks available were provided in form of tons of dry matter per year. The potential biomethane yields per year were also provided in the database, but they were not used, as it was preferred to find and use own average values from literature. No grading scale was used for this indicator, as the availability is already reflected by the sub-questions "Biomethane volume and corresponding energy value" and "Amount and value of bio-fertilizer".

Geographical and physical accessibility

For this sub-question, data on the actual geographical location of the feedstocks in the region could not be found. However, a source of information which was available is regional density maps of the sites of feedstocks production (or handling, in the case of OMSW) realized in 2018 from one of the GoBiom project partners, the Inter-Departmental Centre for Research in Environmental Sciences (CIRSA) of the University of Bologna. From these maps, information about how many production sites and about where they are located in the region was extrapolated. The maps were based on data from ISTAT and from CIRSA's own database. The data refer to the year 2016. QGIS is the software used to create the density maps through the tool "Heatmap". The chosen radius was 15 km and the squared cells have sides of 15 km. The only feedstock for which a density map is not available is wheat straw, which was not assessed for this indicator. The density maps are available in Appendix 2.

Other sources of information which were used are literature articles, materials from the conference "L'era del biometano" from October 11th 2018, and personal communications from key informants. In particular, a phone call with one the authors of the GoBiom maps was conducted, followed by an email exchange with the bioenergy-sector responsible of the regional farmers union "Confagricoltura".

Considering parameters such as extension and connectedness of the areas where the feedstocks are concentrated, it was possible to grade the feedstocks on this aspect. The figure reported in Appendix 1 shows the grading scale used to assess the geographical and physical accessibility of the feedstocks, based on the study from Ammenberg *et al.* (2017).

Feedstock control and competing interests

Based on literature, conference material and personal communications, an overview of the current uses and market of the feedstocks could be gained. A main indicator used was the possibility to sign long-term agreements for the use of the feedstocks. The purpose was to assess how viable is the future use of these feedstocks for production of biomethane, when considering the competing uses and interests for the same feedstocks.

The grading scale for the indicator was taken from Ammenberg *et al.* (2017) and it is reported in Appendix 4.

3.4 Assessment of the technical suitability

To assess the technical suitability of different feedstocks for production of biomethane, the following aspects were investigated based on the study conducted by Ammenberg, Feiz, *et al.* (2017). Literature review was the method used for the results of this section. Values from existing studies were extrapolated and average values were generally taken as definitive result unless one of the values was considered to be more representative than the others.

Feedstocks characteristics and Suitability for anaerobic digestion

Some physical and chemical characteristics of the feedstocks considered were assessed through literature review. In particular, biochemical composition, TS and VS were investigated and reported in the results for this section. Other characteristics such as C/N ratio, pH and degradability were also investigated.

The sub-question "Suitability for anaerobic digestion" looks at the feedstocks physical and chemical characteristics in order to assess to which degree they fit anaerobic digestion requirements as single feedstocks (Ammenberg *et al.*, 2017). The C/N values and the other relevant parameters were taken from literature. As considered by Ammenberg *et al.* (2017), if a feedstock requires a complex and uneconomic pre-treatment in order to enhance anaerobic digestion to a satisfactory level, this aspect is taken in consideration during the grading of the feedstocks. The assessment scale is reported in Table 2.

Table 2. *Grading scale for the indicator "Suitability for anaerobic digestion" from Ammenberg et al. (2017)*

Value	Scale definition
Very good	This feedstock is very digestible and contains all of the components needed for digestion (in suitable amounts and proportions). There is no content of undesirable substances/materials that are inhibiting
Good	This feedstock is very digestible and contains most of the components needed for digestion (in suitable amounts and proportions). This means that additives are needed. There is no content of undesirable substances/materials that are inhibiting.
Satisfactory	This feedstock is rather digestible and contains some of the components needed for digestion (in suitable amounts and proportions). This means that this feedstock needs to be co-digested or additives need to be added. There is may be some content of undesirable substances/materials, but they are not significantly inhibiting.
Poor	This feedstock may be used as complementary feedstock for co-digestion, because it contains one or few of the needed components. There may be some content of undesirable substanecs/materials, but they are not significantly inhibiting.
Very poor	This feedstock cannot contribute to the digestion process, or may act as inhibitor. OR There are some content of undesirable substances/materials that will significantly inhibit the digestion.

Methane yield

A literature review was carried out in order to obtain average values for the methane yield of the selected feedstocks. Some literature studies only reported the biogas yield, which had to be multiplied by the average methane content (percentage of methane within the biogas) in order to obtain the biomethane yield. The average methane content of the feedstock was generally reported by the same article providing with the methane yield, but if not provided then it was assumed as the average value obtained from the other sources. The grading scale from Ammenberg *et al.* (2017) was applied to the yields of the feedstocks and is reported in Table 3.

Table 3. *Grading scale for biomethane yield from Ammenberg* et al. *(2017)*

Value	Scale definition *(m^3 CH_4/ton VS)*
Very good	≥ 600
Good	400-600
Satisfactory	200-400
Poor	50-200
Very poor	≤ 50

Biomethane volume and corresponding energy value

This sub-question relates the theoretical biomethane yields to the availability per year of the selected feedstocks in the region. By multiplying the two parameters, a value corresponding to the total potential biomethane was obtained (millions m^3CH_4/year). In order to adopt the grading scale from Ammenberg *et al.* (2017), the biomethane amount was converted in energy unit (GWh/year). The unit conversion was done by using the energy outputs reported in Table 4, which were self-calculated assuming a lower heating value of 34.812 MJ/Nm^3 of biomethane (Svenskt gastekniskt center, 2012).

Table 4. *Energy output obtainable from the selected feedstocks*

Feedstock	Energy output (GWh/ton VS)
OMSW	4.099
Cow solid manure	1.915
Cow liquid manure	1.861
PSW	5.343
Wheat straw	2.267
Whey	2.704
Wine by-products	1.516

The grading scale adopted for the sub-question is reported in Table 5. The generic scale definition was adopted for the case of each feedstock and the potential biomethane production was compared to the Regional 2030 energy targets.

Table 5. *Grading scale for biomethane amount (from Ammenberg* et al.*, 2017)*

Value	Scale definition (generic level)	Scale definition (case-specific)
	Biomethane production from the estimated available amounts of feedstock	Biomethane production in comparison to existing / planned production
Very good	≥ 500 GWh / year (≥ 50 million Nm^3 / year)	> 70 %
Good	300 - 500 GWh / year (30 - 50 million Nm^3 / year)	40 – 70 %
Satisfactory	100 - 300 GWh / year (10 – 30 million Nm^3 / year)	10 – 40 %
Poor	10 - 100 GWh / year (1 -10 million Nm^3 / year)	1 – 10 %
Very poor	≤ 10 GWh / year (≤ 1 million Nm^3 / year)	≤ 1 %

Nutrient content

The Nitrogen (N) and Phosphorous (P) contents of the raw feedstocks are the indicators considered for this sub-question. Nutrient content is defined as the amount (kg) of Total Nitrogen (N) and Total Phosphorous (TP) per ton of DM in the raw feedstock. Given that covered storage of the digestate is assumed for this study, nitrogen losses in form of ammonia are discarded.

The scale in Figure 1 from Ammenberg *et al.*, (2017) was adopted in order to grade the feedstocks based on the nutrient content. VL stands for very low, L stands for low, M for medium, H for high and VH for very high. VP stands for very poor, P for poor, M for medium, G for good, VG for very good. A very high nutrient content per ton of feedstock is judged to be "very good" for the purpose of this study. However, a conscious use of the digestate is required, since the excessive and inefficient spreading of digestate can lead to adverse effects such as eutrophication and acidification.

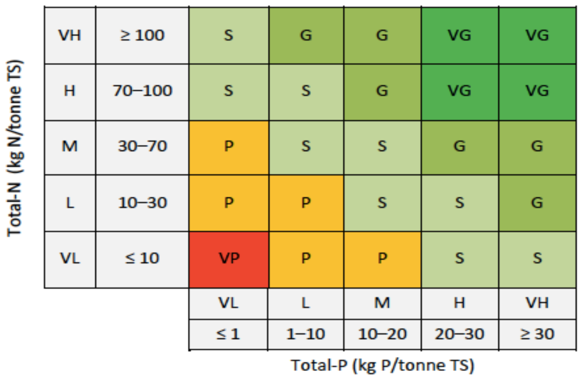

Figure 1. Grading scale for the feedstocks' nutrient content from Ammenberg *et al.* (2017)

Amount and value of bio-fertilizers

The amount of bio-fertilizer which can be produced every year at regional level is calculated and evaluated based on the gross nutrient amount. In order to calculate the amount of bio-fertilizer, the specific nutrient content is applied to the theoretical availability of the feedstocks in the region. The scale is reported in Figure 2. The upper threshold of 4000 tons of N and 2500 tons of P was set by Ammenberg *et al.* (2017) as a result of a participatory consultation with Swedish farmers and biogas producers, which was maintained for this study.

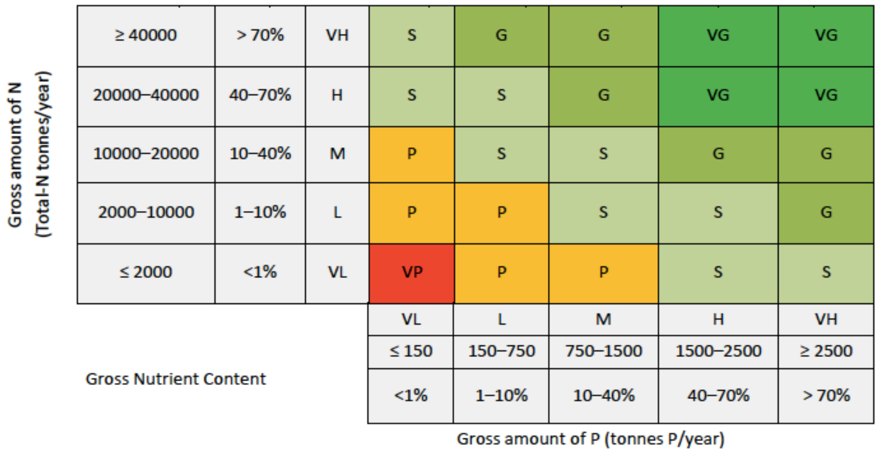

Figure 2. Grading scale for amount and value of bio-fertilizers from Ammenberg *et al.* (2017)

Suitability for bio-fertilizer

The evaluation of the feedstocks based on their suitability for production of bio-fertilizers took into consideration the presence of undesirable substances (i.e process inhibitors and heavy metals) or materials (i.e plastics) associated to each feedstock. The amounts expected to be found in the digestate (high or negligible amounts), as well as their persistency (easy, relatively easy or not easy to degrade/remove), are the parameters considered for the evaluation. Literature studies, regional and national regulation on the issue were the main sources of information. The grading scale utilized, taken from Ammenberg *et al.* (2017) is reported in Appendix 5.

3.5 Assessment of environmental sustainability

3.5.1 Energy balance

The energy balance was calculated by relating -in form of ratio (PEIO ratio)- the Primary Energy inputs to the final energy outputs, occurring throughout the life cycle stages of biomethane production.

For this sub-question, the recommendations from Ammenberg *et al.*(2017) were followed. The assessment included all life-cycle stages -except collection- which are needed to produce biomethane and co-product. The production of 1 MJ of biomethane from each feedstock was taken as functional unit.

Concerning the final energy output (denominator of the ratio), the lower heating value (LHV) of 1 Nm^3 of biomethane was considered in accordance with the guidelines of the European Renewable Energy Directive (RED). The LHV considered is 34,812 MJ according to Svenskt gastekniskt center (2012). The LHV was multiplied by the yield associated to 1 ton of fresh feedstock. The yields are feedstock-specific and they are reported in Section 4.2.2 of the results.

Concerning the Primary energy inputs along the production chain, for Primary Energy it is meant an unconverted and untransformed energy flow as intended by Berglund & Börjesson (2006). The assumptions made for the energy inputs calculations of the baseline scenario are the following:

- All the feedstocks are residues or wastes, therefore energy inputs prior to the collection of feedstock (i.e energy required for production or cultivation) should not be included (Berglund & Börjesson, 2006);
- The energy inputs related to the collection of feedstocks is not accounted for, due to lack of homogeneous data and to the high variability of conditions within a regional context;
- Transport of feedstocks is assumed to happen by trucks fuelled with gasoline. The associated energy inputs refer to a distance of 20 km which includes the empty return of the truck (Berglund & Börjesson, 2006);
- Mechanical pre-treatment is assumed to take place for all the feedstocks in order to reach a Total Solids (TS) content of 12%. In the case of feedstocks with higher TS than 12% treatment with screw press and adding of water is assumed, in the case of feedstocks with lower TS treatment with screw press and recirculation of the excess water is assumed (Pöschl *et al.*, 2010);
- The amount of incoming feedstock resulting from the mechanical pre-treatment is directly proportional to the TS content and it originates an equivalent amount of digestate;
- Heat pre-treatment (sterilization) is assumed to take place for OMSW and PSW at respectively 70 and 133°C for 1 hour and 20 minutes according to Pöschl *et al.* (2010);
- Heat demand during the pre-treatments, digestion and upgrading processes is met by utilization of part of the raw biogas produced, through boiler, assuming that 1 m^3 of biogas with 60% of CH_4 content corresponds to 6 kWh of energy (Svenskt gastekniskt center, 2012) and that 1 MJ of biogas corresponds to 1.3 MJ PE (Berglund & Börjesson, 2006);
- Electricity demand during digestion and upgrading processes is met by utilization of the electricity grid, whose electricity is provided by the Italian electricity mix intended as in the report by Caputo, 2018);
- Electricity demand associated to anaerobic digestion is intended as centralized and mesophilic anaerobic digestion;
- All raw biogas which is not used for heating is upgraded to biomethane through membrane technology as in (Valtieri & Saccani, 2014)

- Digestate is mechanically separated in liquid and solid phases through screw-press technology and partly recirculated in the anaerobic digestion (liquid phase), while the rest (solid phase) is transported and spread as fertilizer;

Values from existing studies on the energy balances of the selected feedstocks were used for the purpose of calculating the PE inputs for the baseline scenario. In the absence of values for the same exact feedstocks, values referring to comparable feedstocks in terms of characteristics (i.e TS) were taken as reported in footnote. Table 6 summarizes which PE values were used and from which author. A screen-shot with the excel calculations for the PEIO ratio is reported in Appendix 6.

Table 6. *Values used for baseline scenario PE inputs*

	Unit	**Value**	**Source**
Transport feed-stocks	MJ/Km*ton	Feedstock specific[a]	(Pöschl *et al.*, 2010)
Pre-treatment elec-tricity	MJ/ton	32	(Pöschl *et al.*, 2010)
Pre-treatment heat	MJ/ton	Feedstock specific[b]	(Pöschl *et al.*, 2010)
A.D. heating	MJ/ton	110	(Berglund & Börjesson, 2006)
A.D. electricity	MJ/ton	66	(Berglund & Börjesson, 2006)
Upgrading heat	MJ/ (CH_4) m^3	0	(Valtieri & Saccani, 2014)
Upgrading electric-ity	MJ/ (CH_4) m^3	1.008	(Valtieri & Saccani, 2014)
Digestate separa-tion	MJ/ton	4.3	(Pöschl *et al.*, 2010)
Loading digestate (solid, liquid)	MJ/ton	3.78; 2.5	(Berglund & Börjesson, 2006)
Transport digestate (solid, liquid)	MJ/km*ton	3.5; 2.5	(Berglund & Börjesson, 2006)
Spreading digestate (solid, liquid)	MJ/ton	14; 17	(Berglund & Börjesson, 2006)

= OMSW 1.8; Manure 2.8; Slaughterhouse waste (paunch content) 2.1; Straw 6.9; Whey (assumed from grease separator sludge) 2.1; Wine residues (assumed from pomace) 2.7; [b] = OMSW 80.64; PSW 113.4;

The PEIO ratio is applied to the grading scale from Ammenberg *et al.* (2017), which is reported in Table 7. The scale was used to grade the energy balance of the feed-stocks, adopting a rounding up in the allocation of the grade considering that the collection step in the life cycle of the feedstocks was excluded from the calculations, likely leading to slightly lower estimations compared to Ammenberg *et al.* (2017).

Table 7. *Grading scale for the energy balance of the selected feedstocks (from Ammenberg* et al.*, 2017)*

Value	Scale definition
Very good	PE input is less than 20% of the final energy output
Good	PE input is between 20 and 33% of the final energy output
Satisfactory	PE input is between than 33 and 50% of the final energy output
Poor	PE input is between 50 and 100 % of the final energy output
Very poor	PE input is more than the final energy output

3.5.2 Climate impact

The climate impact of biomethane production from the selected feedstocks is assessed by the indicator Greenhouse gas (GHG) emissions savings, which compares emissions related to the process of biomethane production ($E_{\text{biomethane}}$) to the emissions related to a baseline fossil reference (indicating average supply and combustion emissions of a fossil fuel, expressed as E_{fossil}), as it is recommended by the Annex V of RED and by Ammenberg, Feiz, *et al.* (2017). The emissions savings (E) were calculated using the following formula and expressed in percentage form:

$$E = \frac{E\,fossil - E\,biomethane}{E\,fossil} \qquad (1.)$$

GHG emissions were expressed as grams of CO_2-equivalent emissions per MJ of upgraded biomethane produced. CH_4, and N_20 emissions were converted to CO_2 equivalent through the conversion factors reported in Table 8, which are in accordance with the IPCC 4th report (Giuntoli *et al.*, 2015).

For the fossil emissions (E_{fossil}), the baseline reference of 94.1 gCO_2 / MJ was used to account for the emissions related to supply and combustion of fossil fuels (Council of The European Union, 2015; Ammenberg *et al.*, 2017) . In addition to this value, the baseline reference for emissions related to supply and combustion of natural gas (CNG) was also considered and assumed to be 71.7 gCO_2 / MJ according to Giuntoli *et al.* (2015).

In order to calculate the GHG emissions associated to the production of biomethane ($E_{\text{biomethane}}$) from the different feedstocks, the guidelines contained in the EU RED were followed for the baseline scenario of this report. According to the RED guidelines, the allocation of GHG emissions related to the production and combustion of biofuels was done with a life cycle approach. A well-to-weel type of assessment, based on actual conditions of the case study, was conducted excluding local environmental impacts as anticipated in Section 3.2.

For the GHG emissions allocation, the process was considered as a refinery-type system since the digestate separation and recirculation of the liquid fraction was assumed. This allocation method implies that all the GHG emissions occurring throughout the process, including digestate management emissions, are allocated to biomethane and do not have to be divided among co-products based on their LHVs (Manninen *et al.*, 2013). A graphic representation of this allocation method was created by Manninen *et al.* (2013) and is reported in Figure 3.

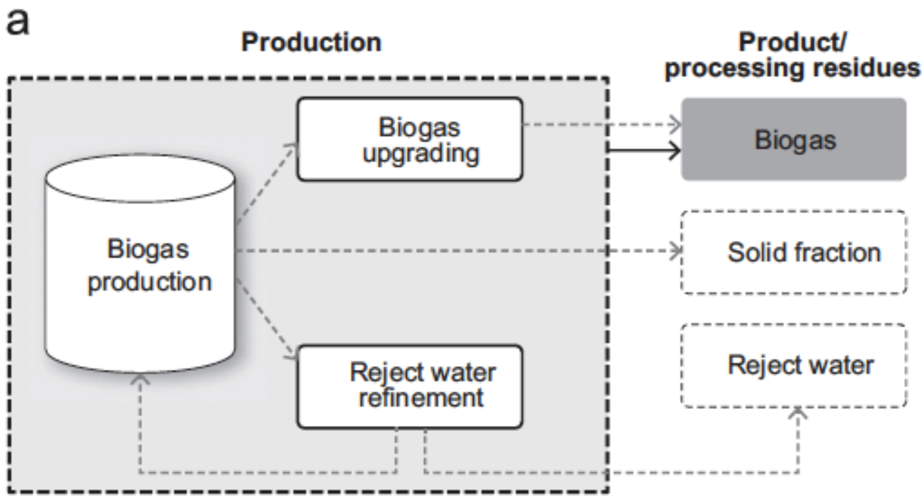

Figure 3. GHG emissions allocation method. The grey arrows with a dashed line indicate material flows while the black solid lines represent emissions (taken from Manninen *et al.*, 2013).

The calculation of the GHG emissions was obtained by accounting for all direct and indirect emissions occurring within the system boundaries and in accordance with the outlined allocation method. The same assumptions made for the calculation of the energy inputs were adopted also for the calculation of the GHG emissions. In addition to those assumptions, also the following assumptions were made:

- Biogenic emissions from the end use of biomethane (combustion) are not accounted for, being all feedstocks wastes or residues;
- All digestate produced was considered to be stored in closed storage tanks, according to the regional regulations, and to be mechanically separated in liquid and solid phases;
- A percentage of 3% of the biomethane produced is assumed to escape to the atmosphere as flared (2%) or leaked (1%) biomethane during the production cycle (Romano *et al.*, 2017);

The values used for the calculation of the GHG emissions throughout the process of biomethane production are reported in Table 8. In Appendix 7, a screenshot with the excel calculations made for the sub-question is reported.

Table 8. *Sources of GHG emissions, amounts and CO_2 equivalent conversion factors*

Gas	Cause of emission	Unit	Amount	Conversion factor	Source
CO_2	Diesel for transport	g/MJ	93.9	1	(Giuntoli *et al.*, 2015)
CH_4	Biogas for heat	g/MJ	0.0028	25	(Giuntoli *et al.*, 2015)
N_20	Biogas for heat	g/MJ	0.0011	298	(Giuntoli *et al.*, 2015)
CH_4	Methane leakage	g/MJ	0.03	25	(Giuntoli *et al.*, 2015)
CO_2	Electricity consumption	g/MJ	86.97	1	(Caputo, 2018)
CO_2	CNG for heating	g/MJ	66.54	1	(Giuntoli *et al.*, 2015)

Once that the GHG emissions and the emissions savings were determined, the feedstocks were graded based on the grading scale reported in Table 9, which was taken from Ammenberg *et al.* (2017).

Table 9. *Grading scale for the indicator GHG emissions savings (from Ammenberg* et al.*, 2017)*

Value	Scale definition
Very good	≥ 60 % (This fuel leads to much lower GHG emissions than petrol. 60% corresponds to the limit for RED from 2018 and onwards)
Good	50 – 60% (This fuel leads to much lower GHG emissions than petrol)
Satisfactory	35 – 50% (This fuel leads to much lower GHG emissions than petrol and is significantly better than natural gas)
Poor	15 – 35% (This fuel leads to significantly reduced GHG emissions in comparison with petrol, but it is not significantly better than natural gas)
Very poor	≤ 15 % (This fuel does not lead to significantly reduced GHG emissions in comparison with petrol

3.5.3 System expansion

In addition to the RED based assessment, a system expansion was applied to the system boundaries of the climate impact. The following GHG emissions, occurring or avoided, were assessed:

Fertilizer credit

The avoided GHG emissions associated to the supply of mineral fertilizer replaced by the digestate are included. This indicator is expressed with negative sign because it is an avoided emission of GHG. The unit, as for the other GHG emissions, is gram of CO_2 equivalent. The framework for the allocation of the fertilizer credit was a 2015 report from the EU Joint Research Centre (JRC) (Giuntoli *et al.*, 2015).

The supply-related GHG emissions for N fertilizers was set to 3977.5 g CO_2 eq/kg fertilizer (Giuntoli *et al.*, 2015). The assumptions are that: the nitrogen mineral fertilizer consists of a mix of urea (36%) and nitrogen ammonium (64%), which are partly (75% and 8%) imported from outside the EU. GHG emissions caused by acidification after spreading of the mineral fertilizer are not included. The supply-related GHG emissions for phosphorous pentoxide (P_2O_5) fertilizers in Europe are assumed to be 1176.1 g CO_2 eq. per kg of fertilizer (ibid.) .

The amount of mineral fertilizers which can be substituted by digestate was calculated based on the estimated nutrient content of the solid fraction of digestate produced by each feedstock. Anaerobic digestion was assumed to not alter the nutrient content of the raw feedstocks (Bachmann *et al.*, 2014), which therefore was assumed to remain the same in the digestate. The efficiency of screw-press digestate separators was considered in order to determine the amount of nutrients contained in the solid part of the digestate after the separation of the two phases. Concerning the separation efficiency, it was assumed that 17% of the Total Nitrogen (TN) and 21,8% of the P_2O_5 present in the digestate remains in the solid fraction after separation (Drosg *et al.*, 2015); (CRPA, 2017). It was assumed that the amounts of nitrogen mineral fertilizer and phosphorous mineral fertilizer which are replaced correspond to the amount of TN and of TP in the solid digestate expressed as a grams per MJ produced. The avoided GHG emissions associated to mineral fertilizer replacement were calculated by multiplying the amount of fertilizer replaced by the supply-related GHG emissions value provided by Giuntoli *et al.* (2015).

Manure credit

The manure credit corresponds to the downstream avoided GHG emissions associated to storage of manure during conventional management (without anaerobic digestion). In fact, it is common practice, also in the case study, to not use a closed facility for storing animal manure. This practice is a cause of emission of GHG due to fermentation processes taking place in the manure stock piles. According to the deliverable 5.3 from the project BIOSURF (Majer *et al.*, 2016), manure credit can be estimated as 99.77 g CO_2 eq. / MJ, corresponding to the amount of GHG emissions which are avoided by producing 1 MJ of biomethane and directly spreading or storing the digestate in closed tanks. This particularly high value applies for biomethane plants provided with closed storage tanks for the digestate (as required by the regional regulation). It does not apply for solid cow manure nor for biomethane plants which are not provided with closed storage for digestate; in both cases the avoided emissions are assumed to be much lower and were not included in the assessment.

Feedstock replacement

Upstream GHG emissions related to the change of the current use of the feedstocks were also considered. Particularly those feedstocks which are currently being used as animal feed were considered due to the indirect GHG emissions for feed replacement to which they are associated. According to the section 3.1 of the results, the only feedstock used as animal feed is milk and cheese by-products. It was assumed that the feedstock would be replaced by barley for 50%, while the remaining 50% is not used for animal feed. One kilogram of feedstock was assumed to correspond to 1.07 kilograms of barley due to the TS difference (Tufvesson *et al.*, 2013). The value of 450 g CO_2 eq. related to the supply process of barley was assumed and used to calculate the upstream GHG emissions associated to the replacement of the feedstock (ibid.)

3.5.4 Sensitivity analysis

A sensitivity analysis was conducted for the climate impact in the baseline scenario and in the system expansion. Some of the parameters characterized by uncertainty were changed in order to account also for alternatives to the assumed conditions in the baseline scenario and to observe the consequent variation on the results. The parameters which were changed are outlined in the following paragraphs.

A change in the transportation distances for feedstock and digestate transport was applied. The assumed distance (20 km) between feedstock location and plant, as well as the assumed distance (20 km) between plant and field for digestate spreading, was increased to 50 km.

A variation in the technology for digestate separation was also considered. Decanter centrifugation was assumed as an alternative to screw press separation. This is associated to a higher separation efficiency but to higher costs and energy needs (Drosg *et al.*, 2015). For decanter separation the PE needs (74.3 MJ PE/ton) provided by Pöschl *et al.* (2010) were assumed.

A change in the use of liquid digestate was applied. Instead of assuming recirculation within the system, spreading of the liquid fraction as fertilizer was assumed for the system analysis. For the energy balance and for the climate impact, the extra steps related to handling of the liquid digestate (loading, transport and spreading) were accounted for in this scenario, also according to the values from Pöschl *et al.* (2010) and to the assumptions made for the baseline scenario. The difference in yields compared to the baseline scenario was disregarded, even though it could be assumed that yields in the spreading of the liquid digestate scenario might be lower as recirculation and energy recovery from the liquid digestate do not take place.

The effect of lowering to 1% and increasing to 5% the amount of leaked methane throughout the process was also observed.

4 Results

The results are presented in this chapter. The three research questions are assessed, respectively, in Sections 4.1, 4.2 and 4.3. Every sub-question is presented in a different sub-section. In Section 4.4, an overview of the findings is provided with the results presented in aggregated form.

4.1 Feedstocks availability

4.1.1 Amounts

The theoretical amounts of feedstocks available in Emilia-Romagna in 2016 are reported in Table 10, according to Regional Database of Wastes and By-products created during the activities of the GoBiom project.

Table 10. *Selected feedstocks availability in Emilia-Romagna*

Feedstock	**Range (tons TS/year)**	**Average (tons TS/year)**
OMSW	9 000 – 22 000	15 500
Cow manure (total)	659 000 – 1 480 000	1 069 500
Solid cow manure	309 000 – 1 022 00	665 500
Liquid cow manure	201 000 – 609 000	405000
PSW	11 000 – 19 000	15 000
Wheat straw	364 000 – 482 000	423 000
Whey	42 000 – 115 00	78 500
Wine by-products	84 000 – 145 000	114 500

4.1.2 Control and competition over the feedstocks

The selected feedstocks have currently various uses in the context of the study area. Most of the feedstocks are being partly used for different purposes than production of biomethane.

OMSW is collected and bio-treated in order to produce compost for almost the entirety of it. However the market price of compost is quite low, with prices ranging between 5 and 15 € for unpacked ton of compost (Centemero, 2010). It has been demonstrated the possibility to integrate the production of compost and anaerobic digestion with mutual benefit (Giacetti *et al.*, 2011). A small part of OMSW is already being anaerobically digested, with five waste treatment plants equipped with anaerobic digesters in the region (Zinoni *et al.*, 2017).

Manure is mainly spread to agriculture. At least 90% of the manure produced is returned to the field after a period of stabilization.

PSW are only partly utilized. Bone material is used in conventional and organic agriculture as phosphorous-rich fertilizer (Greggio, 2018b). Blood is also used in agriculture as fertilizer. A percentage between 7 and 10% of PSW is edible for human consumption -liver and guts- and has a market demand (Riva *et al.*, 2013). The remining of PSW is either grinded and used for animal feed, or it is not used in any way (Greggio, 2018b).

Straw is generally collected and sold or used on farm as animal bedding or as mulch, or it is left in the field in order to improve soil fertility (Greggio, 2018b; Giannoccaro *et al.*, 2017). Today there is straw abundancy and quite low market prices for it, however the price of the feedstock tends to be dependent on its scarcity and it is expected to increase in the case of an emerging bio-energy market (Giannoccaro *et al.*, 2017).

Milk and cheese by-products are generally transformed in products for human consumption (i.e ricotta cheese from sweet fraction of whey), for the extraction of proteins, or for animal feed. It is estimated that only 5% of the milk and cheese by-products has no use; this fraction includes acidic whey, permeate whey and expired or unsold products (Reale, 2008). At large milk processing plants, whey is usually dried and used as feedstock for animal feeding or more recently by the agri-food and pharmaceutical industries (Frigon *et al.*, 2009). However, in small-scale Italian milk or cheese producers, whey is not recuperated and has to be treated along with other generated wastewaters, since the small quantity produced does not justify the significant cost of the equipment needed (i.e for the preparation of whey powder) (ibid).

Wine residues are partly used for extraction of molecules and for distillery (roughly 50%), and partly spread to field often without being previously composted (roughly 50%) (Greggio, 2018b). In the case of some distilleries, anaerobic digestion is already integrated in the production process (Riva *et al.*, 2013). Other treatments methods, more marginal in the context of Emilia-Romagna, include pyrolysis and gasification as intended by Zhang *et al.* (2017).

The possibility of control over the feedstocks depends on the profitability of the uses competing with anaerobic digestion and on the characteristics of the feedstock. Energy content, degradability and possibility to transport and store the feedstock influence the type and the length of contract which is possible to sign for the use of the feedstock (Caliceti, 2018). For all the feedstocks considered, the most common length for the contracts of use between agricultural feedstocks producers and biogas/biomethane producers is between 3 and 5 years (ibid.). For OMSW contracts of use tend to be long-term, in some cases over 20 years (Centemero, 2018).

The feedstocks are graded in Table 11 by applying the grading scale from Ammenberg *et al.* (2017) to the presented findings.

Table 11. *Control and competing interests over the selected feedstocks*

Feedstock	**Note**	**Grade**
OMSW	No realistic competing option for productification and valorization of the feedstock better than anaerobic digestion. Long-term control (7 years) over the feedstock can be easily gained.	**Very Good**
Cow manure	No realistic competing option for productification and valorization of the feedstock. It is reasonable considering a period between 3 and 5 years for the contract of use.	**Good – Very Good**
PSW	Some competing options for productification and valorization of the feedstock. It is reasonable considering a period between 3 and 5 years for the contract of use.	**Good**
Straw	Some competing options for productification and valorization of the feedstock. It is reasonable considering a period between 3 and 5 years for the contract of use.	**Good**
Whey	Some competing options for productification and valorization of the feedstock. It is reasonable considering a period between 3 and 5 years for the contract of use.	**Satisfactory**
Wine by-products	Some competing options for productification and valorization of the feedstock. It is reasonable considering a period between 3 and 5 years for the contract of use.	**Good**

4.1.3 Geographical and physical accessibility

The density of feedstocks production sites in the region is shown in the maps reported in the Appendix 1. OMSW treatment sites are widespread across the region, with about half of the regional territory characterized by 6 to 14 treatment sites in the radius of 225 km^2 and the other half by less than 6. The distribution of the other feedstock production sites is less homogeneous, with a high concentration in the provinces of Modena, Reggio-Emilia and Parma (western part of the region) for cow manure, whey and PSW. The remaining provinces are all characterized by the presence of less than 25 production sites for cow manure, whey and PSW in the radius of 225 km^2 of their territory. Wine by-products production sites are mostly concentrated in the provinces of Cesena, Bologna, Modena and Reggio-Emilia, where 2 to 14 production sites in the radius of 225 km^2 can be found. The remaining provinces are characterized by 2 or less production sites in the radius of 225 km^2.

The feedstocks are graded in Table 13 by applying the grading scale from Ammenberg *et al.* (2017). In the grading scale (reported in Appendix 1) a correlation between grades and most suitable scale for the biomethane plant is suggested.

Table 13. *Geographical and physical accessibility of the selected feedstocks*

Feedstock	**Note**	**Grade**
OMSW	Large share of the feedstock is located in small/connected areas, but a small share is spread over large/unconnected areas.	**Good**
Cow manure	Most of the feedstock is located in small/connected areas and in easily accessible form.	**Very good**
PSW	Significant share of the feedstock is spread over large/unconnected areas.	**Satisfactory**
Straw	Not Assessed.	-
Whey	Significant share of the feedstock is spread over large/unconnected areas.	**Satisfactory**
Wine by-products	Most of the feedstock is produced in few places after that grape from large areas is collected. Easily accessible form.	**Good**

4.2 Technical suitability of the selected feedstocks for production of biomethane and nutrients recycling

4.2.1 Feedstock characteristics and Suitability for anaerobic digestion

The main feedstock characteristics are presented in Tables 14a and 14b. The average values were used in the report for calculations and assessment of several indicators. It can be noted a substantial difference in the amount of Total Solids (TS) among the feedstocks. A low amount of TS, as in the case of whey, implies that most the wet weight comes from the water content; vice versa, a high amount of TS, such as in the case of wheat straw, implies that there is little water content in the feedstock. Literature suggests that 12% is the optimal percentage of TS for feedstocks entering the digestors; therefore it is common practice to dilute or to suck out water from the feedstocks before anaerobic digestion in order to reach a similar percentage of TS (Berglund & Börjesson, 2006; Pöschl *et al.*, 2010; Ammenberg *et al.*, 2017). As it will be showed in the Environmental Section, the amount of TS in the feedstock is also relevant from an energy and environmental point of view (Berglund & Börjesson, 2006; Pöschl *et al.*, 2010). All the feedstocks have a VS percentage higher than 75% of the TS in average.

Table 14a. *Feedstock characteristics of OMSW, solid and liquid cow manure and PSW*

Feedstock	**TS (% of mass)**	**VS (% of TS)**	**Source**
OMSW	20	90	(Reale *et al.*, 2009)
	33	83.70	(Svenskt g., 2012)
	26.5	**86.85**	
Manure (Solid)	18	75	(Reale *et al.*, 2009)
	22	77	(Shah *et al.*, 2012)
	20	**76**	
Manure (liquid)	8	76,6	(Pöschl *et al.*, 2010)
	8.4 [c]	75,9 [c]	(Pagliari & Laboski, 2013)
	8.2	**76.6**	
PSW	15[a]	90[a]	(Reale *et al.*, 2009)
	16[a]	92[a]	(Svenskt g., 2012)
	53.1	75.2	(Riva *et al.*, 2013)
	53.1	**75.2**	

[a] = Not feedstock-specific, but refers to the category of the feedstock (slaughterhouse waste); [b] = refers to blood fraction only; [c] = self calculated as average of more values;

Tabell 14b. *Feedstock characteristics of wheat straw, milk and cheese industry by-products (whey) and wine by-products*

Feedstock	**TS (% of mass)**	**VS (% of TS)**	**Source**
Wheat straw	93.1	76.8	(Mancini *et al.*, 2018)
	94	92.7	(Sambusiti *et al.*, 2013)
	92.69	84.24	(Jaffar *et al.*, 2016)
	93.26	**84.58**	
Whey	6.86	91.1	(Dinuccio *et al.*, 2010)
	5.08	89	(Comino *et al.*, 2012)
	5	86	(Reale *et al.*, 2009)
	5.97	**90.05**	
Wine by-products	47	82	(Reale *et al.*, 2009)
	61.4	90.7	(Dinuccio *et al.*, 2010)
	49.12	**88.17**	

[a] = Not feedstock-specific, but refers to the category of the feedstock (slaughterhouse waste); [b] = refers to blood fraction only; [c] = self calculated as average of more values;

Concerning the suitability for anaerobic digestion, biochemical composition and C/N ratio of every feedstock were investigated.

OMSW is composed for the majority by cellulosic components (23%) and sugars / starch (22%), followed by fats (18%), proteins (12%) and lignin (5%) (Alibardi & Cossu, 2015). Overall, the degradability of OMSW is high and the C/N ratio is suitable (between 20 and 30) (Puyuelo *et al.*, 2011; Zeshan *et al.*, 2012; Divya *et al.*, 2015). Pasteurization and technical pre-treatment of OMSW is required before anaerobic digestion. Undesirable materials tends to be found in the OMSW of the region, with a high degree of variability. The feedstock is assessed as “good” concerning the suitability for anaerobic digestion.

Despite the scarce information found about biochemical composition of manure, a protein content of 18% is assumed, as well as a variable content of undigested cellulosic components (Grazie, 2018). The feedstock is digestible or rather digestible and the C/N ratio tends to be less than 20 for both solid and liquid manure (Fabbri & Piccinini, 2012; Shah *et al.*, 2012; Divya *et al.*, 2015; Insam *et al.*, 2015). Overall, cow manure is considered as “satisfactory” concerning suitability for anaerobic digestion.

PSW have high content of proteins (~ 50%) and fats (35 – 40 %), which are associated to high methane potential but also to risks for the stability of anaerobic digestion process. The C/N ratio is variable depending on the part the animal (between 4 and 37) (Edström *et al.*, 2003; Cuetos *et al.*, 2010). Degradability is good for most of the fractions included, except for bones and bristles (Reale *et al.*, 2009). The feedstock is graded as "satisfactory-good" for this indicator.

It was noticed how straw and wine residues have similar biochemical compositions, with predominance of cellulosic components and quite high percentages of lignin (Sambusiti *et al.*, 2013; Jaffar *et al.*, 2016; Mancini *et al.*, 2018). Lignin and cellulosic components such as cellulose and hemicellulose are problematic substances for anaerobic digestion and technical pre-treatments are necessary in order to ensure the degradation of those substances during the process. For straw, the C/N ratio tends to be higher than 30, up to 100 or more (Divya *et al.*, 2015; Ammenberg *et al.*, 2017; Paul & Dutta, 2018; Zahan *et al.*, 2018). For wine by-products, the C/N ratio is usually between 20 and 30, or a little lower than 20 (Ferrer, 2001; Brunetti *et al.*, 2012; Da Ros *et al.*, 2016; Pellera & Gidarakos, 2017). Considering these aspects, the suitability for anaerobic digestion for both the two feedstocks is considered as "poor".

Whey's most important components from the anaerobic digestion point of view are proteins (18%), fats (5-10 %) and sugars (70-80 %) (Frigon *et al.*, 2009; Comino *et al.*, 2012). The feedstock is easily degradable (Comino *et al.*, 2012). Fat, lactose and sodium chloride might be removed during the processes of milk and cheese production (Reale *et al.*, 2009). However in the case of cheese production, lactose is left in the whey fraction according to other sources (Prazeres *et al.*, 2012; Mollea *et al.*, 2013). The C/N ratio of milk and cheese residues is generally higher than 30, as in the case of cheese-whey wastewater reported by Prazeres *et al.* (2012). Concerning the suitability for single digestion of the feedstock, the acidic pH constitutes a problem for the micro-organisms involved in the processes. Due to this fact, milk and cheese residues are considered as "very poor" for this indicator, but suitable for co-digestion mixtures.

4.2.2 Methane yield

The theoretical yields associated to each feedstock are reported in Tables 15a and 15b. For informative purpose, the range of temperature (mesophilic or thermophilic) considered in the literature studies consulted is reported along with the yield values. Mesophilic conditions correspond to the range 30-42°C and thermophilic to 42-57°C.

None of the feedstocks was assessed as Very Bad in terms of yields according to the adopted grading scale. Starting from one ton of feedstock, pig slaughter wastes bring the highest amount of biogas and methane. OSMW is associated to the second highest yields. However studies from literature report quite different results OMSW yields, as it is reflected upon in the discussion. The lowest yields are associated to anaerobic digestion of wine by-products and cow manure . According to Fabbri *et* *al.* (2015), grape marc is the fraction with the highest methane potential among the fractions usually available as residues from wine making; particularly, the greatest methane yield was obtained from a white grape marc (0.273 ml CH_4/gVS), grape seed gave the second highest methane production (186.91 ml CH_4/gVS), followed by red grape marc (156.85), white grape skins (140.25 ml CH_4/gVS), stalks (140.25 ml CH_4/gVS) and red grape skins (101.28 ml CH_4/gVS).

Table 15a. *Theoretical biogas (G_0) and methane yield (B_0) of the first 3 selected feedstocks. Standard deviation is expressed in parenthesis.*

Feedstock	G_0 *(m³ biogas/ ton VS)*	B_0 *(m³ CH_4/ ton VS)*	Notes	Source	Grade
OMSW	700	385	General	(Reale *et al.*, 2009)	
	936[c]	557	Mesophilic	(Carlsson *et al.,* 2009)	
	401[c]	160	Thermo-philic	(Zeshan *et al.*, 2012)	
	823[c]	502	Mesophilic	(Alibardi & Cossu, 2015)	
	680[c]	408	Mesophilic	(Pöschl *et al.*, 2010)	
	730	438	General	(Giuntoli *et al.*, 2015)	
	710	447	Mesophilic	(Svenskt gastekniskt, 2012)	
	830[c]	494	Mesophilic	(Browne *et al.*, 2014)	**Good**
	726 (147)	**424 (112)**		**Average**	
Cow solid manure	250	156	General	(Reale *et al.*, 2009)	
	376[c]	210	General	(Linville *et al.*, 2015)	
	322	161	Mesophilic	(Greggio et al., 2018)	
	473[c]	264	Mesophilic	(Moody *et al.*, 2011)	**Poor-Satis-factory**
	390	199	General	(Giuntoli *et al.*, 2015)	
	362 (74)	**198 (39)**		**Average**	
Cow liquid manure	300	165	General	(Giuntoli *et al.*, 2015)	**Poor-Satis-factory**
	350	192	General	(CRPA, 202)	
	325 (25)	**179 (14)**		**Average**	
PSW	775[b]	503[b]	General	(Reale *et al.*, 2009)	
	855.50	760	Mesophilic	(Edström *et al.*, 2003)	
	625[b]	394[b]	Mesophilic	(Svenskt gastekniskt, 2012)	**Good**
	752 (95)	**553 (153)**		**Average**	

[b] = refers to the whole category to which the feedstock belongs; [c] = self calculated using own average % of CH4 based on literature;

Table 15b. *Theoretical biogas (G_0) and methane yield (B_0) of the last 3 selected feedstocks. Standard deviation is expressed in parenthesis.*

Feedstock	G_0 (m³ biogas/ ton VS)	B_0 (m³ CH_4/ ton VS)	Notes	Sources	Grade
Wheat straw	356[c]	204	Mesophilic	(Sambusiti *et al.*, 2013)	
	416[b]	212[b]	Mesophilic	(Dinuccio *et al.*, 2010)	
	478[c]	274	Mesophilic	(Mancini *et al.*, 2018)	
	420[b,c]	240[a,b]	Mesophilic	(Moody *et al.*, 2011)	
	420[c]	241[a]	Mesophilic	(Paul & Dutta, 2018)	
	418 (39)	**234 (25)**		**Average**	**Satisfac-tory**
Whey	330	173[c]	General	(Reale *et al.*, 2009)	
	663[c]	359	Mesophilic	(Tufvesson *et al.*, 2013)	
	953	501	Mesophilic	(Dinuccio *et al.*, 2010)	
	405[c]	227[a, d]	(40°)	(Moody *et al.*, 2011)	
	750	450	General	(Fabbri & Piccinini, 2012)	
	620 (228)	**338 (140)**		**Average**	**Satisfac-tory**
Wine by-products	300	176[c]	General	(Reale *et al.*, 2009)	
	250[e]	116[e]	Mesophilic	(Dinuccio *et al.*, 2010)	
	225[f]	98[f]	Mesophilic	(Dinuccio *et al.*, 2010)	
	327	168	Mesophilic	(Fabbri *et al.*, 2015)	
	390	224	Mesophilic	(Da Ros *et al.*, 2016)	
	298 (58)	**157 (45)**		**Average**	**Poor**

[a] = self-calculated as average of more values; [b] = refers to the whole category to which the feedstock belongs; [c] = self calculated using own average % of CH4 based on literature; [d] =refers to cheese whey lactose permeate (TS =22-30); [e] = refers only to grape marcs; [f] = refers only to grape stalks;

4.2.3 Biomethane volume and corresponding energy value

The amounts of potential biomethane, expressed in volume and energy terms, which can be produced every year based on the amounts of feedstocks available are reported in Table 16. Due to the high availability of the feedstocks in the region, manure and straw can contribute the most to this indicators.

The amount of biomethane which the Region is aiming to achieve by 2030 (2850 GWh) is not very distant from the theoretical amount (2514 GWh) of biomethane producible from the six feedstocks considered in this assessment (Caselli, 2018).

Table 16. *Amounts of biogas and biomethane potentials per year from selected feedstocks in Emilia-Romagna*

Feedstock	**Biogas potential based on literature yields (million N m^3 / year)**	**Biomethane potential based on literature yields (million N CH_4 m^3 / year)**	**Energy potential (GWh / year)**	**Grade**
OMSW	12.96	7.71	74.55	**Poor**
Cow solid manure	317,16	100,19	968.83	**Very good**
Cow liquid manure	185.29	59.64	576.73	**Very good**
PSW	14.99	6.23	60.24	**Poor**
Wheat straw	209.184	83.84	810.73	**Very good**
Whey	45.08	19.77	191.18	**Satisfactory**
Wine by-products	38.75	15.83	153.08	**Satisfactory**
TOT	**416.77**	**260.05**	**2514.68**	

4.2.4 Nutrient content

The nutrient content of the raw feedstocks is presented in Tables 17a and 17b. The results indicate quite a low nutrient content for most of the feedstocks, with values of Total Nitrogen (TN) often lower than 30 kg/ton of total solids and Total Phosphorous (TP) often below 10 kg/ton of total solids. Therefore, nutrient content appears as a critical aspect for all feedstocks, with PSW performing slightly better and wheat straw performing the worst.

Table 17a. *Nutrient content for the feedstocks OMSW, Cow manure, PSW and wheat straw.* Standard deviation is expressed in parenthesis.

Feedstock	NTK (Kg/ton TS)	TP (Kg/ton TS)	Source	Grade
OMSW	38,50	4	(Carlsson & Holmström, 2009)	
	32	4	(Cecchi *et al.*, 1991)	
	25.10 [a]	3.80 [a]	(Alibardi & Cossu, 2015)	
	17.75	-	(Zeshan *et al.*, 2012)	
	28	5	(Kubler & Rumphorst, 1999)	
	34	-	(Giuntoli *et al.*, 2015)	
	29.22 (6.7)	**4.18 (0.47)**	**Average**	**Poor- Satisfactory**
Cow solid manure	29	-	(Fabbri & Piccinini, 2012)	
	-	11.70	(Güngör *et al.*, 2007)	
	24	-	(Reale *et al.*, 2009)	
	-	9.30	(Barnett, 1994)	
	36	-	(Giuntoli *et al.*, 2015)	**Poor – Satisfactory**
	38.20	-	(Shah *et al.*, 2012)	
	30.53	-	(Cano *et al.*, 2014)	
	31.54 (5.07)	**10.5 (1.2)**	Average	
Cow liquid manure	59.50	11.50	(Pagliari & Laboski, 2013)	
	54	-	(Fabbri & Piccinini, 2012)	**Satisfactory**
	56.75 (2.75)	**11.50 (0)**		
PSW	86.95 [a]	14.49	(Edström *et al.*, 2003)	
	30 [b]	-	(Fabbri & Piccinini, 2012)	
	65	-	(Blazy *et al.*, 2014)	**Satisfactory - Good**
	60.65 (23.45)	**14.49 (0)**	**Average**	
Wheat straw	9.10	0.60	(Jaffar *et al.*, 2016)	
	11.20	-	(Mancini *et al.*, 2018)	
	7	0.64	(Funke *et al.*, 2013)	**Very poor**
	9.10 (1.71)	**0.62 (0.02)**	**Average**	

[a] = self-calculated as average of more values; [b] = refers to the whole category to which the feedstock belongs; [c] = refers to whey wastewater; [d] =calculated considering a density of 1.012 g/cm^3 taken from Comino *et al.* (2012); [e] = the calculation does not follow TKN methodology

Tabell 17b. *Nutrient content for the feedstocks whey and wine by-products*

Feedstock	NTK (Kg/ton TS)	TP (Kg/ton TS)	Source	Grade
Whey	5[e]	8	(Tufvesson *et al.*, 2013)	
	18.30	-	(Dinuccio *et al.*, 2010)	
	2.10	-	(Comino *et al.*, 2009)	
	23	-	(Fabbri and Piccinini, 2012)	
	18.21[c, d]	13.46 [c, d]	(Frigon *et al.*, 2009)	
	11.31[d]	-	(Ghaly, 1996)	**Poor-Satisfactory**
	12.98 (7.54)	**10.73 (2.73)**	**Average**	
Wine by-products	17.30	1.8	(Ferrer, 2001)	
	30	-	(Brunetti *et al.*, 2012)	
	18.40	4.125	(Da Ros *et al.*, 2016)	
	20	-	(Greggio et al., 2018)	
	19.90 [f]	-	(Dinuccio *et al.*, 2010)	
	23[g]	-	(Dinuccio *et al.*, 2010)	
	21.43 (4.21)	**2.96 (1.16)**	**Average**	**Poor**

[a] = self-calculated as average of more values; [b] = refers to the whole category to which the feedstock belongs; [c] = refers to whey wastewater; [d] =calculated considering a density of 1.012 g/cm^3 taken from Comino *et al.* (2012); [e] = the calculation does not follow TKN methodology; [f] = refers only to grape marcs; [g] = refers only to grape stalks;

4.2.5 Amount and value of bio-fertilizers

The amount of nutrient content available in the digestate producible from the selected feedstocks in a year is estimated in Table 18. The values were obtained by relating the nutrient content of each feedstocks with its theoretical availability. "TN" corresponds to total nitrogen and "TP" to total phosphorous. Manure is associated to the highest potentials concerning this indicator.

Table 18 *Gross nutrient content*

Feedstock	TN (Tons/year)	TP (Tons/year)	Grade
OMSW	453	65	**Very Poor**
Cow solid manure	20 990	7 207	**Very Good**
Cow liquid manure	22 984	4 657	**Very Good**
PSW	910	217	**Poor**
Wheat straw	3 849	262	**Poor**
Whey	1 018	84	**Very Poor**
Wine by-products	2551	299	**Poor**
TOT	**52 756**	**12 792**	

4.2.6 Suitability for bio-fertilizers

From a technical point of view, digestate from OMSW is characterized by higher heterogeneity than digestate from agricultural residues (Giacetti *et al.*, 2011). According to Ammenberg *et al.* (2017), digestate obtained from OMSW can be associated to the presence of heavy metals. However no specific information for the issue in the region could be found. Concerning the presence of plastics in the digestate, the use of bio-plastics is widespread in Emilia-Romagna but can differ among the municipalities. Therefore, micro-fractions of plastics in the digestate from OMSW might be expected in some cases. Digestate produced from OMSW is less suitable than the other feedstocks from a regulatory point of view, due to a longer authorization process for the use as bio-fertilizer. Considering the regulatory and the technical point of view, OMSW is judged to be Poor in terms of suitability for bio-fertilizer.

Digestate produced from anaerobic digestion of cow manure is more homogeneous than digestate from OMSW. Variations can occur depending on the diet. Compared to raw manure, digestate is considered to contain no or less amounts of undigested vegetable residues and active biological agents (Montesin, 2018). The main threat is the possibility of spreading of clostridium spores. However, considering the findings from Fabbri & Piccinini (2012) the feedstock is considered to be good for this indicator.

No particular issues were found about digestate from the other feedstocks, which are therefore graded as very good.

4.3 Environmental sustainability

4.3.1 Energy balance

The energy balance of the biomethane production from each feedstocks is expressed by the Primary Energy Inputs Outputs (PEIO) ratio and reported in Table 19. Inputs and outputs are expressed as MJ per ton of fresh matter (FM). The results show that PSW and OMSW are the feedstock performing better from an energy point of view. According to the grading scale from Ammenberg *et al.* (2017), biomethane production from PSW and OMSW is associated to good energy balance. The feedstocks performing worst are manures (poor) and milk and cheese industry residues (poor-satisfactory).

Table 19. *PEIO ratio of selected feedstocks*

Feedstock	TOT P.E. INPUTS (MJ/ton FM)	ENERGY OUTPUT (MJ/ton FM)	PEIO ratio	Grade
OMSW	819.88	2959.64	0.28	**Good**
Cow solid manure	565.00	936.89	0.60	**Poor**
Cow liquid manure	301.90	365.01	0.83	**Poor**
PSW	1504.99	5980.99	0.25	**Good**
Wheat straw	2450.90	5910.82	0.41	**Satisfactory**
Whey	255.92	467.42	0.55	**Satisfactory-Poor**
Wine by-products	1201.40	2319.75	0.52	**Satisfactory-Poor**

Concerning the contribution of the different process phases of the process (transport of feedstocks, processing and digestate management) to the total PE inputs of each feedstock, it was observed that the major consumption of energy takes place during the "processing", which includes pre-treatments, anaerobic digestion and upgrading. Transporting of the feedstocks and handling of digestate have much lower impacts on the energy balance than processing for most of the feedstocks, but they influence the energy balance of those feedstocks with very low or very high Total Solids, which are characterized by more consumption of Primary Energy for the transport of, respectively, the raw feedstocks and the digestate.

4.3.2 Climate Impact

The allocation of the GHG emissions associated to the production of 1 MJ of biomethane from the different feedstocks are reported in Figure 4.

The trend assessed for the energy balance is reflected in a very similar way in this sub-question. In fact, the climate impact is dependent on GHG emissions related to consumption of energy. Biomethane produced from manure (especially liquid manure) is associated to the highest GHG emissions per unit (MJ) produced, while PSW to the lowest.

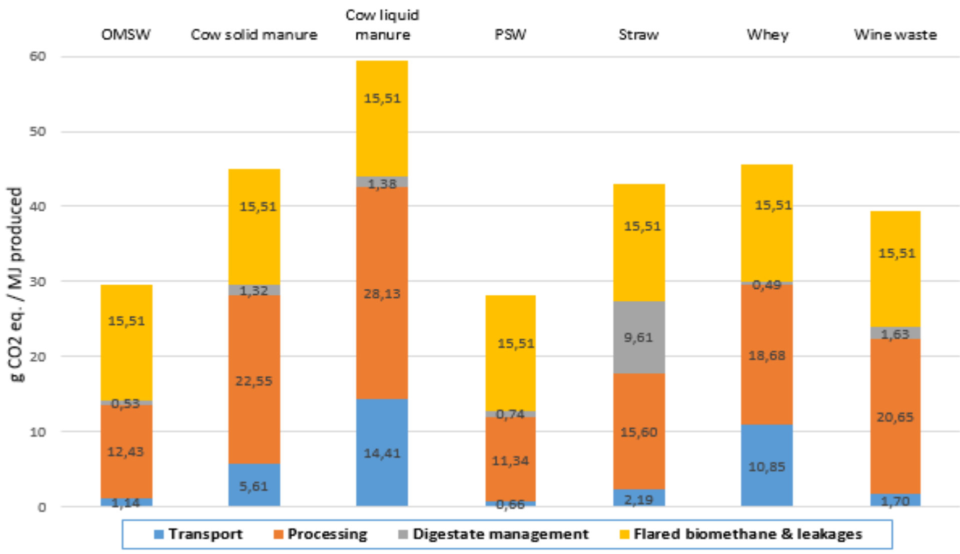

Figure 4. GHG emissions per MJ of biomethane produced

The GHG emissions reduction, compared to fossil fuels, is reported in Table 20 along with the gradings of the feedstocks. It can be observed that all feedstocks but cow liquid manure contribute to at least 50% reduction compared to fossil fuels. The highest reduction is associated to the substitution of fossil fuels with biomethane produced from PSW or OMSW.

Table 20. *GHG emissions reduction*

Feedstock	gCO_2 eq./ MJ	Emissions reduction compared to baseline fossil fuel (%)	Emissions reduction compared to natural gas (%)	Grade
OMSW	29.61	68	58	**Very good**
Cow solid manure	44.99	52	37	**Good**
Cow liquid manure	59.48	37	17	**Satisfactory**
PSW	28.25	70	61	**Very good**
Wheat straw	42.91	54	40	**Good**
Whey	45.53	52	36	**Good**
Wine by-products	39.49	58	45	**Good**

4.3.3 System expansion

By including the upstream and downstream GHG emissions with system expansion, the climate impact associated to the biomethane production and nutrient recycling of the feedstocks varies considerably for some feedstocks. It can be observed in Figure 5 how the avoided GHG emissions from the manure credit in the case of biomethane production from liquid manure diametrically alters the GHG emissions accounting, exceeding by about 40 units the GHG emissions occurring throughout the process and bringing the emissions balance to negative terms. The other factors affect the indicator to a lower extent than manure credit does.

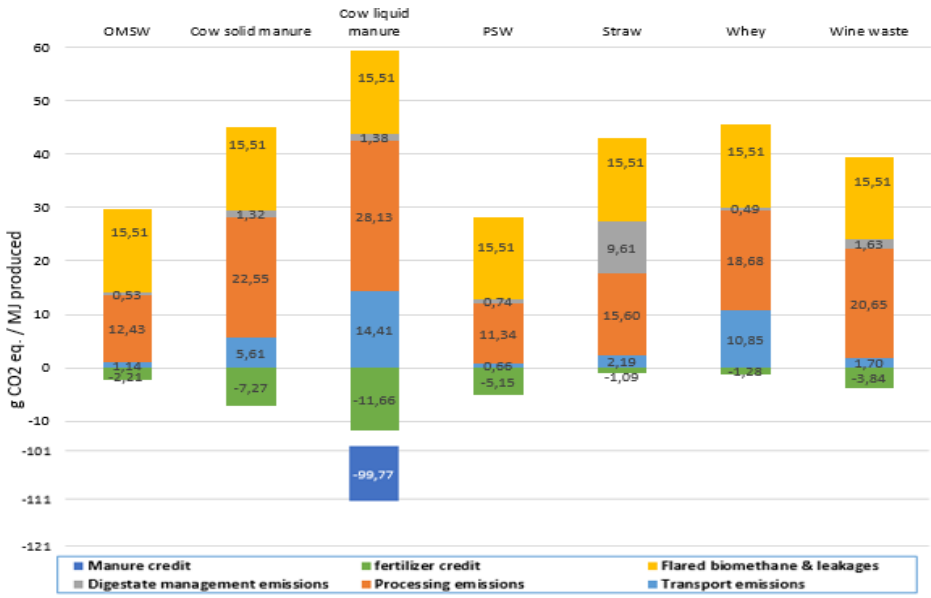

Figure 5. GHG emissions of the feedstocks with system expansion

4.3.4 Sensitivity analysis

The sensitivity analysis is reported in Figure 6. It was noted that a variation in the transport distance for the supply of the raw feedstocks to the plant clearly affects the energy balance of feedstocks characterized by low density such as cow manures, straw and whey more than the other feedstocks. By altering the technology used for the separation of the digestate, the range of variation on the PEIO due to the use of the decanter technology is between 5.51% (straw) to 26.73% (wine wastes). When looking into the possibility of spreading to field the liquid fraction of the digestate along with the solid fraction, the PEIO ratio increases of a variable percentage ranging between 4.20 (straw) and 28.70 (wine wastes).

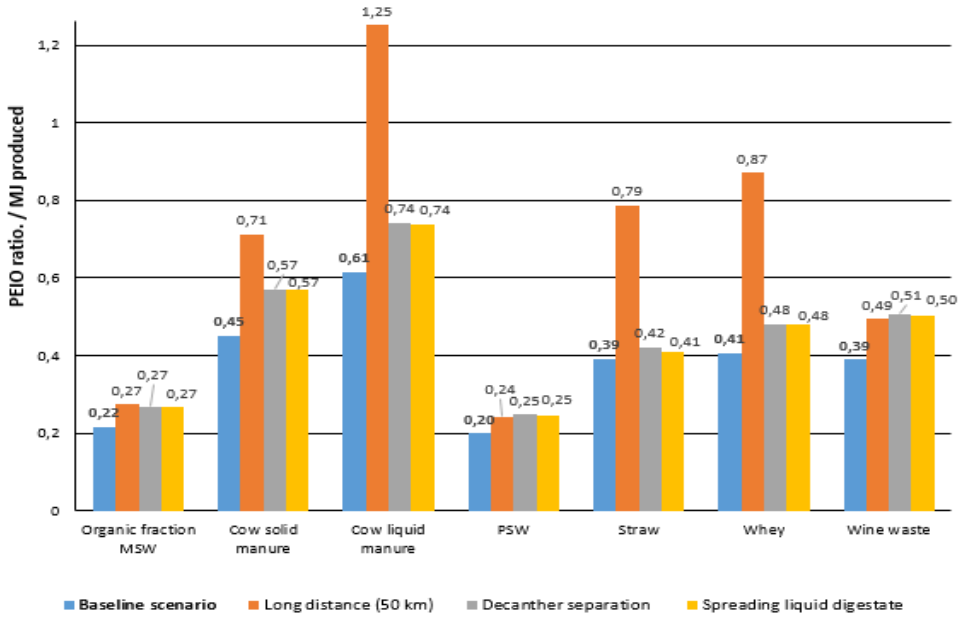

Figure 6. Sensitivity analysis for the PEIO ratio

A sensitivity analysis was also conducted for the indicator "climate impact". In addition to the scenarios adopted in the sensitivity analysis for the PEIO ratio. The biomethane-leakage parameter was also changed assuming both lower (1%) and higher (5%) values and creating two new scenarios. The sensitivity analysis is applied to the amount of GHG emissions per MJ of biomethane produced and is reported in Figure 7. Concerning the long transport distance scenario, the range of variation is the broadest compared to the other scenarios: it can vary from 14.24% (for PSW) to 98.97 (for cow liquid manure). Applying the decanter technology scenario, the range of variation is lower: from 12.93% (whey) to 24.44% (wine wastes). Separation of the digestate with decanter technology increases the fertilizer credit as it is associated to higher separation efficiency than screw press separation, especially for what concerns phosphorous in the solid fraction (Drosg *et al.*, 2015; CRPA, 2017). Spreading liquid digestate as fertilizers is also associated to smaller variations, with a range of variation between 3.16% (whey) and 26.60% (wine wastes). Spreading of the liquid fraction as well as the solid fraction of the digestate also increases the fertilizer credit, since all the nutrients contained in the digestate will reach the soil. Differently, by altering the methane-leakage value, variations for the low methane leakage scenario from 20.67% for cow liquid manure up to 52.67% for OMSW can be obtained, while for the high methane leakage scenario the range of variation goes from 17.12% for cow liquid manure to 36.13% for PSW. In short, the parameters for which the indicator climate impact seems to be most sensitive to are transport distance and methane leakages. However, especially for the transport distance, the impact is dependent on which feedstock is considered.

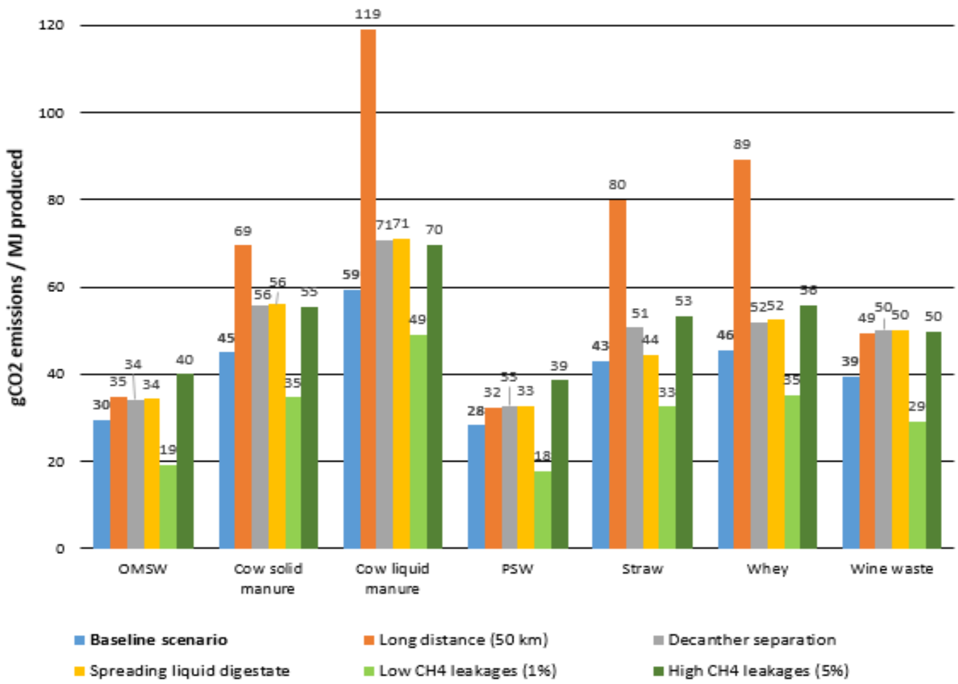

Figure 7. Sensitivity analysis for the climate impact indicator

In Figure 8, the sensitivity analysis is applied to the system expansion scenarios of the climate impact indicator. The baseline scenario (based on RED I guidelines) is also reported for comparison with the system expansion scenarios. It appears clear how the system expansion with spreading of liquid digestate scenario is associated to the lowest climate impact for all feedstocks. This means that, especially for medium-short distances and for OMSW, PSW and wine wastes, the increase in the fertilizer credit from spreading of the liquid fraction of the digestate justifies the extra GHG emissions from increased energy consumption and for transport during the digestate management phase, as long as a low energy-demanding separation technology is adopted. When a more energy-demanding separation technology like decanter centrifuge is adopted, the results suggest that the benefits from a climate impact point of view are lower compared to the other drawn scenarios.

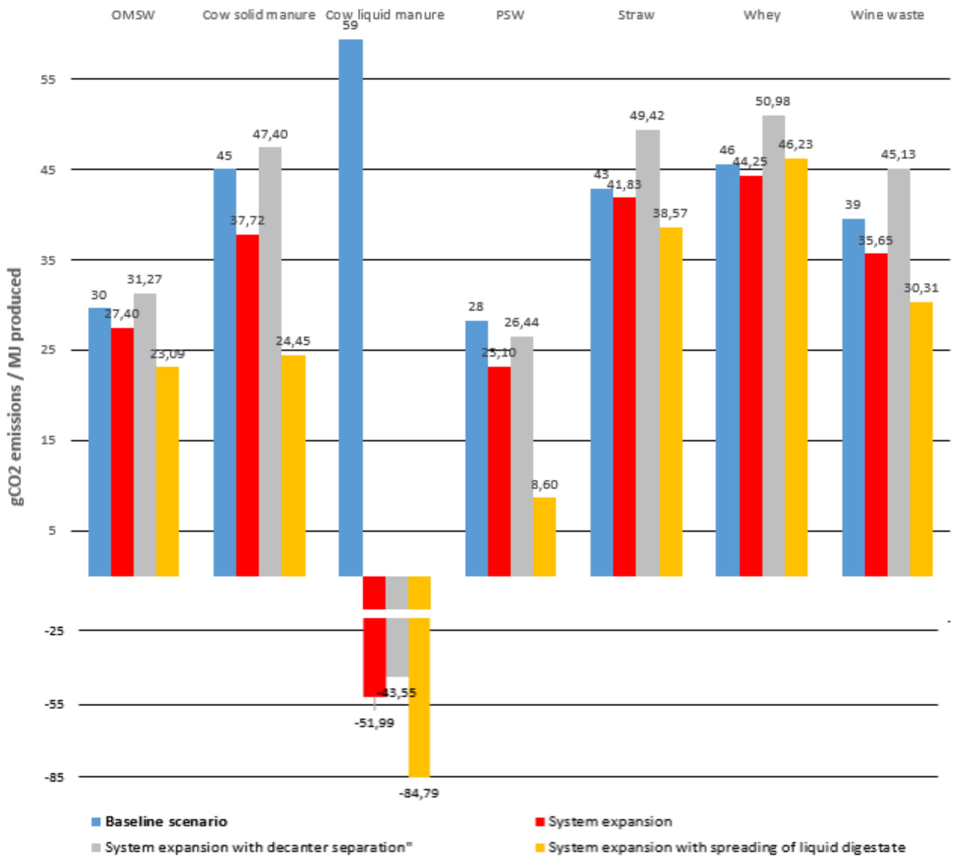

Figure 8. Sensitivity analysis for the system expansion scenario of the climate impact indicator.

4.4 Aggregated results

The results are summarized in Table 21 with the grades coloured from red (bad) to yellow (intermedium) to green (good) and coded as follows: VG = Very good, G = Good, S = Satisfactory, P = Poor, VP = Very poor.

It can be noted how every feedstock has strengths and weaknesses. Overall PSW performs better than the other feedstocks concerning the three areas of interest (availability, technical and environmental suitability). The theoretical availability was not graded but it directly affects the indicators "Amount of biomethane" and "Amount of nutrients", where manure and (to a lower extent) wheat straw performs well.

Table 21. *Aggregated results*

Indicators	**OMSW**	**Cow solid-manure**	**Cow liquid manure**	**PSW**	**Wheat straw**	**Whey**	**Wine by-products**
Interests and control over the feedstock	VG	G - VG	G	G	G	S	G
Geographical and physical accessibility	G	VG	VG	S	-	S	G
Suitability for anaerobic digestion	S-G	G	G	G	P	VP	P
Biomethane yield	G	P-S	P-S	G	S	S	P
Nutrient content	P-S	P-S	S	S-G	VP	P	P-S
Amount of biomethane	P	VG	VG	P	VG	S	S
Amount and value of bio-f.	VP	VG	VG	P	P	VP	P
Suitability for bio-fertilizers	P	G	G	VG	VG	VG	VG
Climate impact	VG	G	S	VG	G	G	G
Energy balance	G	PS	P	G	S	P-S	P-S

5 Discussion

The methodology is critically reflected upon. Overall validity of the assessment method, system boundaries, applicability of the grading scales to the case study, and method used for each indicator are critically reflected and discussed in Section 5.1. Furthermore, the results are grouped by feedstock in Section 5.2 and discussed more specifically in terms of uncertainty and contextualized within the existing literature.

5.1 Critical reflections over the methodology

One of the strength of the multi-criteria assessment (MCA) is that it allows for a broader picture than it is usually given by literature studies, which are often more sectorial or feedstock-specific. This is true even though not all of the indicators which were part of the original assessment method from Ammenberg *et al.* (2017) could be covered. Further studies could address the economic, policy related and social aspects.

A down side of conducting a MCA applied to more feedstocks is the vast amount of information which has to be collected. The majority of data was collected through literature review, therefore the accuracy and certainty of the results is affected by the heterogeneity of the sources consulted. This factor is coupled with the fact that the assessment is applied to a non-specific, rather general scale, which challenges the applicability and the certainty of some parameters due to the variability within the region.

Another factor to be aware of is the "single-feedstock approach" of this assessment. Even though co-digestion of different feedstocks is a very common practice for biogas production, this eventuality is not included in the assessment. Nevertheless, it can be argued that assessing the characteristics of single feedstocks can provide the information necessary for developing good feedstock mixtures for co-digestion. With this in mind, the suitability of the feedstocks for co-digestion with other feedstocks is shortly discusses in the following section.

Furthermore, the methodology is rich in terms of indicators for the technical aspects but it lacks on economic socio-indicators for the feedstock availability section and on local impacts for the environmental section.

For an easier reading, the discussion over the assessment of single indicators is presented in separated sections reflecting the structure of the results.

Feedstocks availability

The estimated availability of feedstocks in the region is judged to be reliable thanks to the experience of the GoBiom project partners. The estimation is enriched by a qualitative discussion on the effective availability based on current uses and interests on the feedstocks. However, there is more uncertainty on this estimation, being it based on personal opinions and dependent on case-specific factors which could not be grasped at regional scale. The geographical and physical accessibility would also need to be analyzed at more local level in order to judge the actual accessibility of feedstocks and the opportunity of developing new biogas plants. In fact, the density maps of production sites do not show the quantities of feedstock produced in each site, so they can only offer indirect information.

Technical suitability

Concerning the applicability of the data from literature review to local conditions, it was assumed that general characteristics of the feedstocks -such as chemical composition, amount of solids and volatile solids, energy content, nutrient content and biogas yields- would be close enough for the purpose of this study, despite the variable origin of the literature studies considered. Especially for some indicators (i.e biomethane yield), there are many possible factors of variability and uncertainty. For these indicators, the amount of sources consulted was abundant in order to obtain representative average values. In the case of nutrient content of the feedstocks, there is uncertainty due to the scarce number of sources which could be found. Also, the indicator does not offer direct information on the nutrient content of digestate, which could vary as pointed out in Section 2.4. The calculations on biomethane and nutrients amount per year are dependent on the values chosen for yields and nutrient content of different feedstocks, therefore they carry the same level of uncertainty.

Concerning the value of digestate as a bio-fertilizer, it is perceived by the author that the MCA methodology set up by Ammenberg *et al.* (2017) lacks on the assessment of the carbon balance, which is an element of interest for soils poor in organic matter such as in the case of Italy. It could have been added an indicator assessing the inputs of carbon from the feedstocks, and the transformation rate during anaerobic digestion. Concerning the suitability for fertilizers, the level of certainty is medium or low due to a lack of specific studies about the feedstocks of the area and to the variability of factors (such as the pre-treatments adopted) when considering a regional scale.

Environmental aspects

Among the factors of uncertainty, there is the choice of the functional unit. It makes a difference if dry matter instead of wet weight is considered, as also if a different unit than MJ per MJ of biomethane produced is considered. For example if the energy balance or the climate impact was calculated based on tons of feedstock treated, without relating them to the energy output, the outcomes of the analysis would be different.

Another factor affecting the environmental assessment is the lack of specific information on the real conditions of the case study, which is not plant-specific and therefore subject to more variability. For example concerning the technology in use there are several ways to pre-treat, digest, upgrade and handling digestate, which can affect differently the outcome of the indicators used. Some of these factors were addressed in the Sensitivity Analysis, however not all of the possible variations could be considered.

Whether digestate should be considered as a by-product, or rather as a co-product of biomethane in a refinery-type of system (with feedback loops between the pathways of the co-products, due to recirculation of part of the liquid digestate in the system) is being debated in literature (Manninen *et al.*, 2013). The origin of this debate is the text of RED itself, which leaves too much room for interpretation on this issue (Manninen *et al.*, 2013). What changes, depending on which of the two interpretations is chosen, is the point in the process when the emissions should be allocated, which influences the outcome of the GHG allocation. In the biomethane-as-main-product interpretation, emissions are calculated right after the separation of biomethane from the digestate; in the refinery-interpretation, emissions allocation should refer to the point after recirculation of the digestate to the digestor (Manninen *et al.*, 2013).

5.2 Discussion over the results

5.2.1 Organic municipal solid waste (OMSW)

As reported in the results, the availability of OMSW is small compared to some of the other feedstocks. If the green fraction of waste and the unsorted fraction of waste would be included, they would add respectively 21 to 38 000 and 32 to 79 000 tons of TS per year (Gobiom, 2017). However, pre-treatments would be necessary in order to improve the digestibility of the green waste and to sort unwanted materials and sanitize the unsorted fraction of municipal waste.

The widespread geographical distribution of the feedstock treatment sites might be directly related to the population density of the region, as shown in the population density map reported in Appendix 3.

OMSW is characterized by a variable composition depending on the area and the time of the year considered by literature studies. Alibardi & Cossu (2015), consider the category of fruits and vegetables to be the major component of OMSW (approximately 50% of the wet weight), followed by the categories of bread and pasta (15 to 20%), of fish, cheese and meet (5%) and by undersieve and other type of waste. Variations on the OMSW mixture can alter the biochemical composition and the amounts of TS and VS. Concerning TS and VS, the values can vary up to 30 % due to the variability of the feedstock composition itself. Concerning the yields, the second highest average value was registered from literature. However there is quite high variability, mainly depending on the composition of the feedstock. All values deviate for less than 20% from the average value, except for one isolated case, which registers a 42.9% lower methane yield. Methane yield depends also on the conditions in which the anaerobic digestion takes place, such as digestor scale, temperature, hydraulic retention time and inoculum used. In a general, laboratory conditions ensure higher yields than in real scale (Svenskt gastekniskt center, 2012). One more factor to consider is also that, generally, not all of the biogas obtainable after anaerobic digestion can actually be upgraded to biomethane, since part of it is often combusted in order to heat the plant. Concerning nutrient content, this might be the weak point of the feedstock. In this report nutrient content was judged to be "poor-satisfactory", but there is more uncertainty on this aspect compared to other feedstocks due to higher variability in the composition of the OMSW, on the pre-treatment technology in use and to the limited number of sources consulted on this aspect. Biomethane production from OMSW performs well in terms of energy balance. The pre-treatments affect the PEIO ratio more than for the other feedstocks, as both heat and electricity are required for pre-treatment and sterilization of the feedstock. The high yield and therefore the high energy output contribute to keep low the PEIO ratio. However the result is affected by the choice of not including the PE inputs related to collection of OMSW, which is generally highly energy consuming compared to the collection of other feedstocks but also very dependent on characteristics such as the geographical context (rural or urban) and the distance range. The results are therefore considered more reliable in this way, but less comparable with studies which have assessed the PEIO ratio of the feedstock including also PE for collection.

The climate impact of biomethane production from OMSW is very low. The feedstock results to not be significantly affected by the parameters considered in the sensitivity analysis.

5.2.2 Cow manure

Cow manure is characterized by the largest availability per year, especially if both liquid and solid cow manure are considered. Comparable feedstocks in terms of characteristics are pig slurries and poultry litter; by including them, the theoretical availability per year could be increased of 373 000 to 728 000 tons (Gobiom, 2017).

There is uncertainty concerning the biochemical composition of the feedstock as no literature covering this aspect could be found. It is assumed that the composition can vary based on the diet, depending if it is beef or dairy cows, on the area and on the type of management (intensive or extensive). Concerning TS and VS, differences depend on which material is taken in consideration. Not always it is stated whether the manure is fresh (less than 3 months) or mature (more than 9 months). If it is fresh, more water and therefore less TS can be expected. The freshness of the manure also affects the content of nutrients, and in particular the form in which nitrogen is brought to the digester. The yields from anaerobic digestion of cow manure are judged to be barely satisfactory or poor, with liquid manure providing slightly higher methane yields than solid manure (Fabbri & Piccinini, 2012). Co-digestion with many others feedstocks is common practice in Italy, since it can increase methane yields and have other beneficial effects. However it should be regarded to avoid practices which can lead to ammonium (NH_3) and foam formation, such as unbalanced mixtures with protein-rich feedstocks, drastic temperature changes and excessive dilutions or re-circulations of the digestate (ibid.). Concerning the suitability of cow manure for anaerobic digestion, a problem often associated to the agronomic use and to the anaerobic digestion of manure is the propagation of the very resistant clostridium spores (Doyle *et al.*, 2015). The issue is relevant for the area, as the performance of cheese making can be severely affected by it. The outcomes of an empirical study conducted on the topic are reported by Fabbri & Piccinini (2012). It is argued that anaerobic digestion of liquid manure as a single feedstock does not increase the number of clostridium spores in the outflow material compared to the inflow, while co-digestion of manure with ensiled crops (both maize and sorghum) does contribute to an increase of spores.

Concerning the energy balance of the feedstock, given the low yields and low energy content associated the PEIO ratio remains low. Compared to another study considering liquid manure (Pöschl *et al.*, 2010), the obtained PEIO ratio results to be in line.

Concerning the climate impact, a huge difference is made by the manure credit in the system expansion. Liquid manure, when the manure credit is not included, is associated to the highest GHG emissions per unit of energy produced. However, when it is included, the climate impact turns negative. The calculations of the manure credit (taken from the project BIOSURF) can be questioned. However, even the minimum manure credit proposed by the authors -applying to biomethane plants which are not provided of closed storage for biomethane- would result in a sensitive variation of the climate impact of the feedstock. Furthermore, manure credit for cow solid manure was not included and therefore cannot be compared. The sensitivity analysis shows a strong sensitivity on the transport distance for both liquid and solid forms of cow manure, but particularly for liquid manure. In the system expansion, the climate impact is also affected very much the digestate use, which can contribute more than in other feedstocks to replacement of mineral fertilizers.

5.2.3 Pig slaughter-house waste (PSW)

The availability of PSW is quite limited but it could be increased by, respectively, 19000 to 29000 and 5000 to 7000 tons per year if poultry and cow residues from animal slaughterhouses would be included (Gobiom, 2017)

The lack of studies on the production of biogas specifically from PSW made it difficult to find specific TS and VS values for the feedstock. Since values from anaerobic digestion of slaughterhouse wastes included also wastes from other animals than pig or only some fractions, there is some, limited, uncertainty over the results obtained for the parameters making use of those values. PSW is associated to the highest methane yield among the feedstocks. One of the reasons for the high yields is generally considered to be the high content of fat and of other energy-rich components in the substrate. One factor affecting the yield from PSW is whether a heat pre-treatment is done or not; heat-treated animal by-products can reach biogas yields up to 75% higher than not treated (Edström *et al.* 2003), pressure pre-treatment can also enhance higher yields (Cuetos *et al.*, 2010). However it should be said that the number of studies available where single-feedstock digestion of PSW is conducted was limited. More common practice is co-digestion with other feedstocks. Co-digestion with both food wastes and liquid manure has proved stable and useful to improve both yields and nutrient content of the digestate (Edström *et al.*, 2003). While the richness in fats of PSW is associated to the risk of excessive foam formation during single-feedstock digestion, co-digestion with diluting substrates (i.e liquid manure) can be helpful to solve the issue by enhancing binding and consequent degradation of the foams (Reale *et al.*, 2009).

The energy balance of PSW is the best performing among the feedstocks. Similarly to wheat straw, PSW are associated to very high yields and very high energy content. This characteristic definitely affects the PEIO ratio, keeping it low, even though PSW is associated to the second-most energy-demanding process compared to the rest of the feedstocks. This is mostly due to the thermal pre-treatment required before anaerobic digestion and to the upgrading electricity demand. Comparing the obtained PEIO ratio with other studies, Pöschl *et al.* (2010) obtained a higher PEIO ratio (0.60), considering paunch content of slaughterhouse waste. However a good amount (16%) of the PE inputs accounted for by Pöschl is related to loading and collecting the raw feedstocks, which are excluded from the boundaries of this report. Another difference between this report and Pöschl's study is that the energy content of the paunch content reported by Pöschl is about half (7.71 GJ /ton DM) compared to the energy content considered for the mixture of PSW in this report (14.45 GJ /ton DM). The difference in the energy content affects greatly the PEIO ratio. The study from Berglund & Börjesson (2006), assessing slaughterhouse wastes in general, takes an intermediate value (9.4 GJ / ton DM) as energy content of the substrate. The resulting PEIO ratio in Berglund & Börjesson (2006) is in line, 0.25.

Also concerning the climate impact, PSW is the best performing feedstock. The sensitivity analysis does not show any major changes after a variation in the parameters considered. It is however interesting how the spreading of liquid digestate results particularly rewarding in terms of fertilizer credit compared to other feedstocks. This might be linked to the fact that PSW is also the most nutrient-rich feedstock, and therefore it pays off more to recycle them by spreading also the liquid fraction of digestate.

5.2.4 Wheat straw

The already large availability of this feedstock in the region is even higher (up to 921000) if straw from other cereals (durum, barley, rice and sorghum) is considered

Wheat straw and other lignocellulosic materials are hardly digestible as single and untreated feedstocks (Paul & Dutta, 2018). However, methane yields and biodegradability of the feedstock can be improved by chemical, physical and mechanical treatments. Compared to what is reported in the table, Mancini *et al.* (2018) have managed to increase the CH4 yield by 11% and 15% through different chemical pre-treatments including organic solvents. However acid and hydrothermal pretreatment is associated to the production of inhibitors, such as phenolic compounds (Paul & Dutta, 2018). Sambusiti *et al.*(2013) claim that heat treatments alone do not improve the yield from wheat straw, while they are effective when combined with alkaline chemical treatments, contributing to methane yield increase up to 67% (341 CH_4 Nm^3/ton TS with 10% NaOH treatment at 100°C). Co-digestion of the feedstock with manure or other feedstocks with low C/N ratio can also increase methane yields from anaerobic digestion (Paul & Dutta, 2018).

Concerning the nutrient content, chemical pre-treatments of the feedstock gave positive results regarding the availability of phosphorous (Jaffar *et al.* 2016). A way to concentrate and to retain nutrients is to treat the digestate with hydrothermal carbonization (HTC) in order to obtain hydro-char. Funke *et al.* (2013) have found out that 60-65% of nitrogen and 77-80% of phosphorous can be recovered with high reproducibility in the hydro-char from wheat straw digestate. Besides retaining nutrients, hydro-char allows to recover residual energy in the digestate if used as fuel instead of as soil ameliorant.

The energy balance of the feedstock is very good despite the high energy inputs required (mostly for upgrading and for handling of the digestate). The reason for this fact can be found in the very high energy output of straw, which is associated to its high methane potential. However it should be noted that the estimation of the Primary Energy requirement for pre-treatment of the feedstock might not be completely accurate, since it refers to mechanical treatment while literature is now focusing also on different types of treatment, such as chemical treatment often combined with heat treatment. Furthermore, if the collection of the feedstock from the field was included in the calculations, the PEIO would increase of a factor of about 8-10% according to the PE demand for collection estimated by Berglund & Börjesson, 2006). Compared to the PEIO ratio of straw contained in the article from Pöschl *et al.* (2010), which is 0.15, the energy balance of the feedstock from this report is definitely higher, while it is line with the estimate (0.46) by Ammenberg, Feiz, *et al.* (2017), which is based on the study from Berglund & Börjesson (2006).

The climate impact of wheat straw is judged to be good in the baseline scenario. While when the transport distance is increased, straw is negatively affected more than other feedstocks.

5.2.5 Milk and Cheese Industry by-product

The reported theoretical availability already accounts for the maximum amount of feedstock available in the region. There is a substantial difference between the theoretical and the real availability of the feedstock due to the current uses of the feedstock.

In literature there is a high discrepancy concerning the methane yield which can be obtain from the feedstock. Partial explanations for the discrepancy could be a difference in the feedstock composition between the values reported in literature, which might or might not include the lactose and protein content. However, the fundamental difference is made by the water content, which is the predominant component of the wet weight of the feedstock. Even though the specific yield is quite high (Dinuccio *et al.*, 2010), the yield associated to the fresh matter is very low compared to the other feedstocks. Concerning co-digestion, Comino *et al.* (2012) report that a mix of 50% cattle slurry and 50% whey with OLR of 2.65 g-VS/l-d can lead to similar yields as for co-digestion of energy crop and livestock waste (343 l-CH_4/kg-VS).

The very low content of Total Solids is an issue for transport, as it is shown in Figure 11 and by the sensitivity analysis. Low TS content also translates in very low energy output per ton of FM of the feedstock. The outcome would be different if the net energy output would be assessed on a dry base instead of on FM base, but it would not reflect correctly what is the real conditions.

Compared to the outcomes of the study on the energy balance of whey permeate from Tufvesson *et al.* (2013), the obtained PEIO ratio in this report results to be higher than what calculated by Tufvesson (0.36). One main difference in the calculations concerns digestate handling, since digestate is not considered to be separated in the study from Tufvesson *et al.* (2013).

5.2.6 Wine-making residues

The good theoretical availability of the wine-making residues is challenged by the problem of seasonality and by the inconvenience of storing the feedstock, which can lead to fermentation processes.

Concerning the suitability for anaerobic digestion, pre-treatments are necessary and different options are possible (Riva *et al.*, 2013). Thermophilic anaerobic digestion has proved useful to increase the methane yield from the feedstock (ibid.). Co-digestion with other feedstocks including wastewater sludge and other agro-industrial residues (i.e residues from the production chain of olive oil) were also associated to improve methane yield and degradability (Da Ros *et al.*, 2016). There is uncertainty concerning the Phosphorous content of the feedstock, given that only few studies have assessed it.

The energy balance of biomethane production from wine residues resulted to be poor-satisfactory. Given the quite high amount of TS and consequently of digestate, the digestate-handling step results to be more energy-intensive than for feedstocks characterized by low amount of TS. Mechanical pre-treatment is considered as part of the processing step of the process, however if different types of pre-treatment would occur they might result in lower or, more likely, higher PE inputs than what is assumed in the report. No studies on the energy balance of biomethane production from the feedstock could be found. The most comparable study considers anaerobic digestion of distillery wastes and the PEIO ratio resulted to be lower, 0.30 (Riva *et al.*, 2013).

Compared to its PEIO ratio, the feedstock performs better from the climate impact point of view. Part of the merit might be allocated to the low PE need, and therefore low GHG emissions, for transport.

6 Conclusions

Opportunity, technical feasibility and environmental sustainability of biomethane production and nutrient recycling from the six feedstocks were assessed in the context of Emilia-Romagna region in Italy. The results suggest that there are strengths and weaknesses for every feedstock considered. In synthesis, a predominance of agricultural feedstocks such as manure and straw was registered in terms of theoretical availability. Other factors such as current uses and seasonality play also an important role and should be taken in consideration, especially for milk and cheese industry and wine industry by-products. From a technical point of view, feedstock suitability for the process of anaerobic digestion, yield, nutrient content and water content, and pre-treatment requirements are important parameters to consider. Concerning the energy and environmental aspects, a correlation between the PEIO ratio and the GHG emissions reduction is noted. The life cycle analysis analysis shows that OMSW and PSW perform better than the other feedstocks for both the indicators. With all the feedstocks except for cow liquid manure, a reduction in the GHG emissions higher than 50% compared to the fossil fuel baseline can be achieved according to the RED accounting method. However a system expansion including indirect GHG emission, such as avoided emissions from storage of liquid manure, can considerably alter the outcomes of the analysis. Overall, the production of biomethane from the six feedstocks can contribute significantly to the achievement of the 2030 energy target for the region and for the recycling of nutrients in agriculture. A more detailed summary of the main findings concerning each feedstock assessed is presented in the next paragraphs.

OMSW represents only a small fraction of the residual feedstocks available every year in the region. It is easily accessible and well distributed. Biomethane production is considered to be among the best management solutions for the valorization of the feedstock and it can be integrated with existing facilities for the production of compost. From the technical point of view, single feedstock digestion is possible and is associated to good specific methane yields. From the studies consulted, the nutrient content of OMSW is poor/satisfactory. An obstacle to overcome concerns the quality of the digestate in terms of heavy metals and plastics if it is intended to obtain the authorization necessary for spreading digestate as bio-fertilizer. From the energy and environmental point of view, OMSW performs very well thanks to the high specific yields it is associated with.

Cow manure is one of the most abundant residual feedstocks in the region. The concentration is higher in some provinces, but a relevant amount of the feedstock is assumed to be available and easily accessible everywhere. Anaerobic digestion competes with direct spreading of manure but it leads to energetic valorization, avoided GHG emissions and more plant-available form of the nutrients. The feedstock is suitable for anaerobic digestion and for the use as bio-fertilizer. The methane yield and the nutrient content are judged to be barely satisfactory but they can be improved through co-digestion with other feedstocks. The energy balance is poor/satisfactory and the emissions reduction is good/satisfactory, depending on the form of manure, with the liquid manure performing worse than solid manure and other feedstocks (unless manure credit from avoided storage emissions is accounted for) and being particularly sensitive to changes in the transport distance.

PSW responds better than all the other feedstocks concerning the technical and environmental aspects. However, the theoretical availability of PSW is little and the possibility of control and accessibility of PSW is good or satisfactory depending on the province. From a technical point of view, the feedstock is suitable for anaerobic digestion and for the use as bio-fertilizer when heat pre-treatment is operated and the process is monitored so that problematics such as foam formation are avoided. The methane yield is the highest among the feedstocks and the nutrient content is considered to be good. From an environmental perspective, energy balance and emissions reduction are both good and not very sensitive to the alteration of the parameters considered in this study.

Straw from soft wheat is an abundant residual feedstock in the region and it can be combined with straw from other cereals in order to reach even higher availability. Competing uses for the feedstock exist but the possibility of control is judged to be good . Concerning the technical aspects, the suitability of straw for single-feedstock digestion is poor, the methane yield is satisfactory, nutrient content is very poor, and the suitability for the use as bio-fertilizer is very good. Pre-treatments and co-digestion with other feedstocks are recommended. From an environmental point of view, the performance of straw is satisfactory in terms of energy inputs/outputs and good in terms of reduction of GHG emissions. However the feedstock is highly sensitive to the transport distance.

Milk and cheese industry by-products are concentrated in few provinces (Modena, Reggio-Emilia and Parma) and they are scarcely available due to existing uses of the feedstock aimed at human consumption or other uses. From a technical point of view, the feedstock is problematic for single-feedstock digestion and is characterized by a high water content. Despite this, satisfactory and good methane yields were obtained in research experiments at laboratory scale. The nutrient content of whey is judged to be poor/satisfactory. From an environmental perspective, the energy balance is poor/satisfactory and the GHG emissions reduction compared to fossil fuel is good. However the feedstock is highly sensitive to changes in the transport distance.

Wine by-products are most abundant in the provinces of Cesena, Bologna, Modena and Reggio-Emilia. The possibility of control and the accessibility of the feedstock are judged to be good. From the technical point of view, pre-treatments are needed in order to pursue single-feedstock digestion. The obtainable methane yield is generally poor compared to other feedstocks and the nutrient content is also considered to be poor, even though the number of studies including nutrient content is limited. No particular issue undermines its suitability for the use as bio-fertilizer. From an environmental point of view, the energy balance of biomethane production from wine by-products is poor/satisfactory and the GHG emissions reduction is good.

Concerning the methodology, the multi-criteria assessment as designed by Ammenberg *et al.* (2017) proved to be a good guiding-framework for systematic analysis and for decision-making in the field of biogas/biomethane. The more specific case study the more accurate results can be expected to be obtained. Including life cycle assessment in the analysis can provide with important insights on the sustainability of the process, but it is also a challenging operation especially if it is desired to include indirect GHG emissions.

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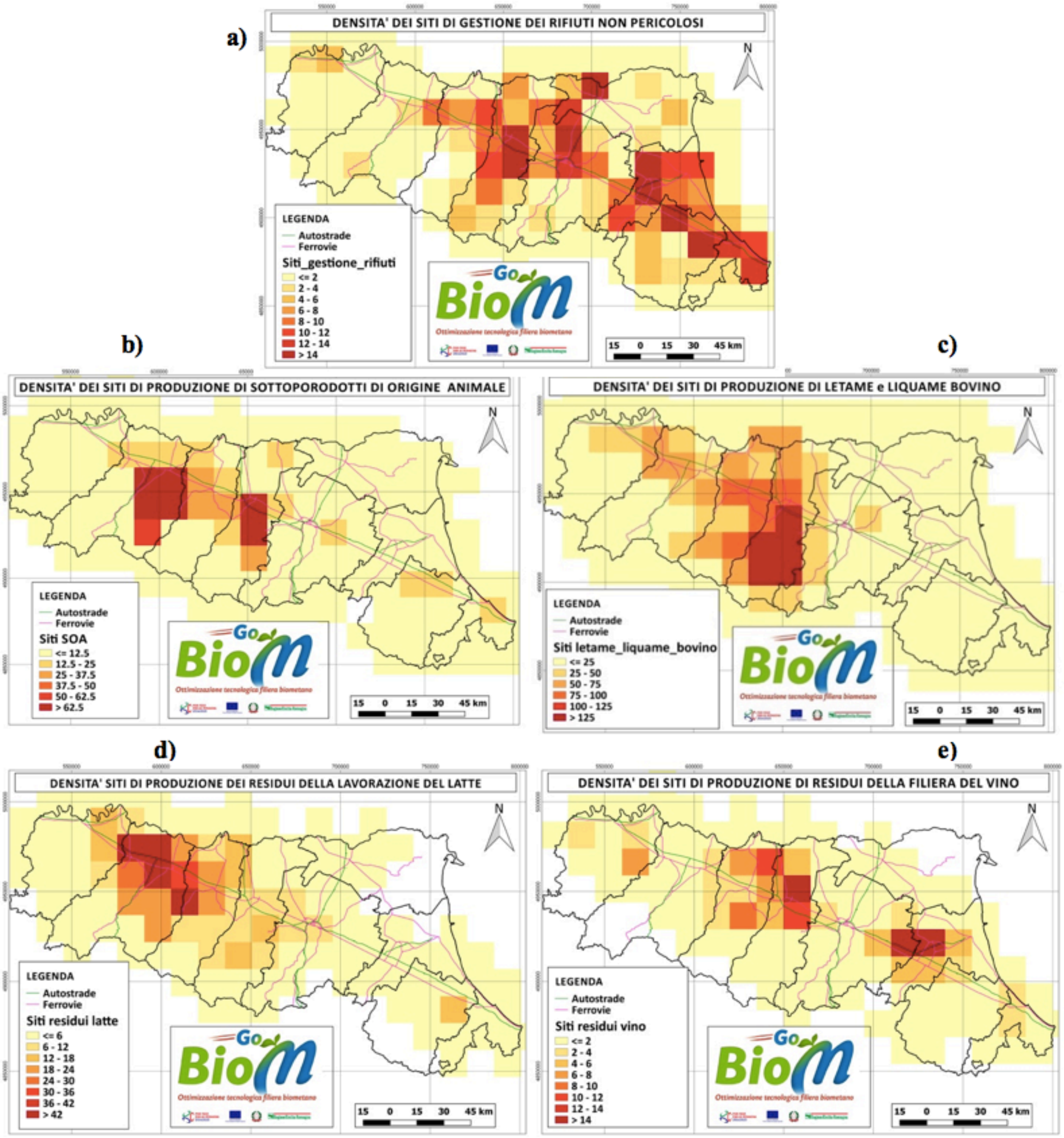
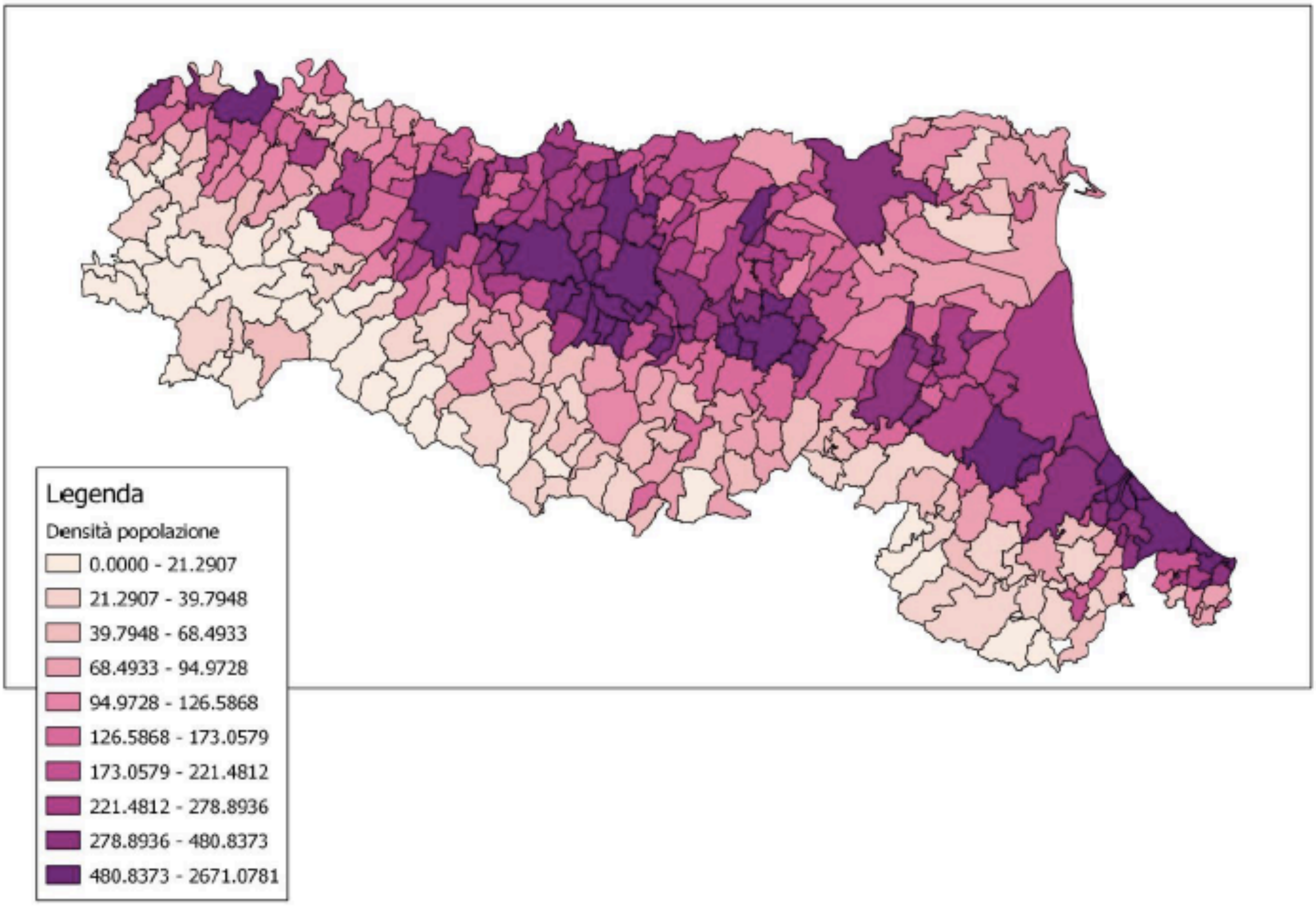
Appendix 1: Grading scale used for geographical and physical accessibility of the selected feedstocks (from Ammenberg *et al.*, 2017)

Value	Scale definition		Remarks
Very good	**Most** of the biomass is located within **small/connected areas** and in such a way/form that it is **easily accessible**. Assuming technological feasibility, biogas production appears **favorable** considering collection and transportation.		
Good	**A large share** of the biomass is located within **small/connected** areas AND in such a way/form that it is **easily accessible**. Assuming technological feasibility, biogas production appears **favorable** within these areas considering collection and transportation.	However, **a small share** of the biomass is spread over **large/unconnected** areas OR has such a form that it is **hard to access**. Even if assuming technological feasibility, biogas production is probably **not reasonable** within these areas considering collection and transportation.	Some large-scale biogas production plants might be possible. For most of the biomass, medium or small-scale biogas plants seem reasonable.
Satisfactory	**A significant share** of the biomass is located within **small/connected areas** and in such a way/form that it is **easily accessible**. Assuming technological feasibility, biogas production is **possible** within these areas considering collection and transportation.	However, **a significant share** of the biomass is spread over **large/unconnected** areas or has such a form that it is **hard to access.** Even if assuming technological feasibility, biogas production is probably **not reasonable** within these areas considering collection and transportation.	Primarily medium or small-scale biogas production seems reasonable for some of this feedstock.
Poor	**A small share** of the biomass is located within **small/connected** areas and in such a way/form that it is **easily accessible**. Assuming technological feasibility, biogas production is **possible** within these areas considering collection and transportation.	However, **a large share** of the biomass is spread over **large/unconnected** areas or has such a form that it is **hard to access**. Even if assuming technological feasibility, biogas production is probably **not reasonable** within these areas considering collection and transportation.	Mainly small-scale biogas production seems reasonable for a small share for this feedstock.
Very poor	**Most** of the biomass is spread over **large/unconnected** areas or has such a form that it is **hard to access**. Even if assuming technological feasibility, biogas production is probably **not reasonable** within these areas considering collection and transportation.		Perhaps a few small-scale biogas plants might be possible, or no production at all.

Appendix 2: Density maps of feedstocks production sites (provided by GoBiom project): (a) *non-dangerous waste* handling sites; (b) *cow manure and cow slurry*; (c) *slaughterhouse waste*; (d) *milk/cheese-industry residues*; (e) *wine-making by-products*.



Appendix 3: Population density map of Emilia-Romagna (from Emilia-Romagna Region website)



Appendix 4: Grading scale for the indicator "control and competing interests over the feedstocks" (from Ammenberg *et al.*, 2017)

Value	Scale definition (generic)
Very good	Existing biogas and biofertilizer producers have control over this feedstock and this is expected to remain for long (at least for 7 years). OR If existing biogas and biofertilizer producers would like to produce biogas from this feedstock, they are able to sign very long term contracts (**at least for 7 years**) to secure the access during this period. Except for biogas and the by-products from that production, there seem to be no realistic competing options for productification and valorization[11]. Regarding control and competition, the terms for access are reasonable considering a period of **at least 7 years.**
Good	If existing biogas and biofertilizer producers would like to produce biogas from this feedstock, they are able to sign long term contracts (**at least for 5 years**) to secure the access during this period. The feedstock might be used for some other applications, why the competition might increase in the near future. Regarding control and competition, the terms for access are reasonable considering a period of **at least 5 years**, but the more long term picture is a bit uncertain.
Satisfactory	If existing biogas and biofertilizer producers would like to produce biogas from this feedstock, they are able to sign short term contracts (**at least for 3 years**) to secure the access during this period. The feedstock might be used for many other applications, why the competition is expected to increase in the near future. Regarding control and competition, the terms for access are reasonable considering a period of **at least 3 years**, but the more long term picture is very uncertain.
Poor	If existing biogas and biofertilizer producers would like to produce biogas from this feedstock, they are only able to sign very short term contracts (**at least for 1 year**) to secure the access during this period. The feedstock is used for some other applications, and many other are possible, why the competition is expected to increase significantly in the near future. Regarding control and competition, the terms for access are only reasonable considering a period of **1 year**, but the more long term picture is very uncertain.
Very poor	Existing biogas and biofertilizer producers cannot get access to this feedstock, because they do not control it AND/OR the competition for it is too tough. Regarding control and competition, this feedstock is not realistic to utilize for biogas production.

Appendix 5: Grading criteria for the indicator “suitability for bio-fertilizers” (from Ammenberg *et al.*, 2017)

Value	Scale definition (generic and case-specific)
	Consider the contaminants in the feedstock and applicable Swedish regulations:
Very good	The feedstock contains **negligible amounts** of undesirable substances/materials and these undesirable materials are **easily degradable** (they are very short-lived) or **easily removed.** *To produce certified biofertilizers is **very likely unproblematic**.*
Good	The feedstock contains **negligible amounts** of undesirable substances/materials and these undesirable substances/materials are **relatively degradable** (they are relatively short-lived) or **relatively easily removed.** OR The feedstock contains **noteworthy amounts** of undesirable substances/materials, but these undesirable substances/materials are **easily degradable** (they are very short-lived) or **easily removed.** *To produce certified biofertilizers is **likely unproblematic**.*
Satisfactory	The feedstock contains **negligible amounts** of undesirable substances/materials, but these undesirable substances/materials are **not degradable** (they are persistent) and are **difficult to remove.** OR The feedstock contains **noteworthy amounts** of undesirable substances/materials, but these undesirable substances/materials are **relatively degradable** (they are rather short-lived) or **relatively easily removed.** OR The feedstock contains **high amounts** of undesirable substances/materials, but these undesirable materials are **easily degradable** (they are very short-lived) or **easily removed.** *To produce certified biofertilizers is **possible, but requires precaution**.*
Poor	The feedstock contains **noteworthy amounts** of undesirable substances/materials, and these undesirable substances/materials are **not degradable** (they are persistent) and **cannot be removed.** OR The feedstock contains **high amounts** of undesirable substances/materials, and these undesirable substances/materials are **not easily degradable** (they are rather persistent) or **easily removed.** *To produce certified biofertilizers is **problematic**.*
Very poor	The feedstock contains **high amounts** of undesirable substances/materials, and these undesirable substances/materials are **not degradable** (they are persistent) and **cannot be removed.** *To produce certified biofertilizers is **not possible**.*

Appendix 6: Excel calculations for energy balance

PE inputs required to produce 1 MJ of biomethane							
Primary Energy (MJ input/MJ produced)	**Organic fraction MSW**	**Cow solid manure**	**Cow liquid manure**	**PSW**	**Straw**	**Whey**	**Wine waste**
Amount of feedstock necessary to get 1 MJ of biomethane (tons)	0,000337878	0,001067352	0,002739649	0,000167196	0,000169181	0,002139409	0,000431082
Amount of feedstock after pre-treatment (tons)	0,000746148	0,001778919	0,001872094	0,000739844	0,001314821	0,001064356	0,001764561
PE transport of substrate (MJ/ton * km)	1,8	2,8	2,8	2,1	6,9	2,7	2,1
Realistic distance (KM)	20	20	20	20	20	20	20
PE transport of substrate	0,012163624	0,059771694	0,15342035	0,007022246	0,023347029	0,115528081	0,01810543
TOT	**0,012163624**	**0,059771694**	**0,15342035**	**0,007022246**	**0,023347029**	**0,115528081**	**0,01810543**
Screw press for desired TS	0,01081211	0,034155254	0,087668771	0,005350283	0,005413804	0,068461085	0,013794613
Heat input for pretreatments	0,027246517	0	0	0,018960065	0	0	0
Process electricity	0,082076303	0,195681143	0,205930291	0,081382818	0,144630331	0,117079152	0,194101703
Process Heating	0,049245782	0,117408686	0,123558175	0,048829691	0,086778199	0,070247491	0,116461022
Upgrading heating	0	0	0	0	0	0	0
PE for upgrading (MJ/m^3)	1,008	1,008	1,008	1,008	1,008	1,008	1,008
Upgrading electricity	0,028955533	0,028955533	0,028955533	0,028955533	0,028955533	0,028955533	0,028955533
TOT	**0,198336244**	**0,376200615**	**0,44611277**	**0,183478389**	**0,265777867**	**0,284743261**	**0,35331287**
Dewatering	4,3	4,3	4,3	4,3	4,3	4,3	4,3
Dewatering	0,003208437	0,007649354	0,008050002	0,003181328	0,005653731	0,00457673	0,007587612
PE loading solid digestate	7	7	7	7	7	7	7
Loading solid digestate (MJ)	0,000208921	0,000535455	0,0005635	0,000383239	0,007510259	7,45049E-05	0,000802875
PE loading liquid digestate	2,5	2,5	2,5	2,5	2,5	2,5	2,5
Loading liquid digestate (MJ)	0,001790756	0,004256065	0,004478984	0,001712738	0,000604818	0,002634281	0,004124661
PE Transport solid digestate	3,5	3,5	3,5	3,5	3,5	3,5	3,5
Realistic distance (KM)	20	20	20	20	20	20	20
Transport solid digestate	0,002089215	0,005354548	0,005635002	0,003832391	0,075102587	0,000745049	0,008028752
PE Transport liquid digestate	2,5	2,5	2,5	2,5	2,5	2,5	2,5
Realistic distance (KM)	20	20	20	20	20	20	20
Transport liquid digestate	0,035815114	0,085121297	0,089579677	0,034254768	0,012096355	0,052685619	0,082493224
Spreading solid d. B&B	14	14	14	14	14	14	14
Spreading solid	0,000417843	0,00107091	0,001127	0,000766478	0,015020517	0,00014901	0,00160575
PE spreading liquid d.(Mj/ton)	17	17	17	17	17	17	17
Spreading liquid d.	0,012177139	0,028941241	0,03045709	0,011646621	0,004112761	0,01791311	0,028047696
TOT	**0,005924417**	**0,014610266**	**0,015375504**	**0,008163436**	**0,103287094**	**0,005545294**	**0,01802499**
TOT PE INPUTS (MJ)	0,216424284	0,450582575	0,614908625	0,198664072	0,392411989	0,405816636	0,38944329
Ratio (I/O)	0,216424284	0,450582575	0,614908625	0,198664072	0,392411989	0,405816636	0,38944329
Cubic meters of upgraded CH4 needed to obtain 1 MJ	0,028725727	0,028725727	0,028725727	0,028725727	0,028725727	0,028725727	0,028725727
CH4 Yield / ton FM	85,01793523	26,91308508	10,48518464	171,8083477	169,7924966	13,42694551	66,63639237
Energy content 1 m3 CH4 (MJ)	34,812	34,812	34,812	34,812	34,812	34,812	34,812
Energy content biogas (MJ / Nm3)	19,8	20,16	19,8	22,14	20,52	18,9	21,24
Biogas used for heating (Nm3)	0,004247196	0,007466466	0,0080004	0,003486307	0,00542174	0,004765126	0,007029614
% CH4	55	56	55	61,5	57	52,5	59
Digestate produced (tons)	0,000746148	0,001778919	0,001872094	0,000739844	0,001314821	0,001064356	0,001764561
Solid fraction of digestate (tons)	2,98459E-05	7,64935E-05	8,05E-05	5,47484E-05	0,001072894	1,06436E-05	0,000114696
Liquid fraction of digestate (tons)	0,000716302	0,001702426	0,001791594	0,000685095	0,000241927	0,001053712	0,001649864
Ts (%) feedstock	26,5	20	8,2	53,1	93,26	5,97	49,12
Ts (%) digestate	4	4,3	4,3	7,4	81,6	1	6,5
Energy output (MJ)	1	1	1	1	1	1	1

Appendix 7: Excel calculations for the climate impact (baseline scenario)

GHG emissions (CO2 eq. / MJ produced)

GHG emissions (gCO2 eq./MJ produced)	OMSW	Cow solid manure	Cow liquid manure	PSW	Straw	Whey	Wine waste
Emissions from diesel combustion	93,9	93,9	93,9	93,9	93,9	93,9	93,9
Emissions for transport of substrate	1,14216426	5,61256211	14,4061709	0,659389	2,192286	10,84809	1,7001
Transport emissions	**1,14216426**	**5,61256211**	**14,4061709**	**0,659389**	**2,192286**	**10,84809**	**1,7001**
Emissions from electrity consumption	86,97	86,97	86,97	86,97	86,97	86,97	86,97
Electricity for pretreatments	0,9403292	2,970482439	7,62455305	0,465314	0,470839	5,954061	1,199718
CNG combustion (CO2 emissions)	66,45	66,45	66,45	66,45	66,45	66,45	66,45
Heat emissions for pretreatments	1,81053105	0	0	1,259896	0	0	0
Emissions from biogas (CH4 & N20) combustion	0,40376	0,3978	0,3978	0,3978	0,3978	0,3978	0,3978
Process Heating	0,01988348	0,046705175	0,08191907	0,019424	0,03452	0,027944	0,046328
Process Electricity	7,13817605	17,01838897	17,9097574	7,077864	12,5785	10,18237	16,88103
Upgrading heating	0	0	0	0	0	0	0
Upgrading electricity	2,51826267	2,518262668	2,51826267	2,518263	2,518263	2,518263	2,518263
Processing emissions	**12,4271824**	**22,55383925**	**28,1344922**	**11,34076**	**15,60212**	**18,68264**	**20,64533**
Dewatering	0,27903779	0,665264296	0,7001087	0,27668	0,491705	0,398038	0,659895
Loading solid digestate	0,0181699	0,046568501	0,04900761	0,03333	0,653167	0,00648	0,069826
Loading liquid digestate (MJ)	0,15574202	0,37014996	0,38953722	0,148957	0,052601	0,229103	0,358722
Transport solid digestate	0,19617729	0,502792022	0,52912665	0,359862	7,052133	0,06996	0,7539
Transport liquid digestate	3,3630392	7,992889791	8,41153164	3,216523	1,135848	4,94718	7,746114
Spreading solid	0,03923546	0,100558404	0,10582533	0,071972	1,410427	0,013992	0,15078
Spreading liquid d.	1,14343333	2,717582529	2,85992076	1,093618	0,386188	1,682041	2,633679
Digestate management emissions	**0,53262044**	**1,315183224**	**1,38406829**	**0,741844**	**9,607432**	**0,48847**	**1,6344**
CO2 eq emissions from 1 g CH4	25	25	25	25	25	25	25
Flared biomethane (g)	0,41365047	0,413650465	0,41365047	0,41365	0,41365	0,41365	0,41365
Leaked biomethane (g)	0,20682523	0,206825233	0,20682523	0,206825	0,206825	0,206825	0,206825
Flared biomethane & leakages	**15,5118925**	**15,51189245**	**15,5118925**	**15,51189**	**15,51189**	**15,51189**	**15,51189**
TOT emissions (gCO2 eq. / MJ)	**29,6138596**	**44,99347704**	**59,4366238**	**28,25389**	**42,91373**	**45,53109**	**39,49173**
Emissions reduction compared to gasoline (supply and combustion)	0,68529373	0,521854654	0,36836744	0,699746	0,543956	0,516141	0,580322
Emissions reduction compared to CNG (supply and combustion)	0,58697546	0,372475913	0,17103732	0,605943	0,401482	0,364978	0,449209

Sveriges Lantbruksuniversitet
Institutionen för energi och teknik
Box 7032
750 07 UPPSALA
http://www.slu.se/institutioner/energi-teknik/

Swedish University of Agricultural Sciences
Department of Energy and Technology
P. O. Box 7032
SE-750 07 UPPSALA
SWEDEN
www.slu.se/en/departments/energy-technology/